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PERSPECTIVES IN TECHNOLOGY

Solar Energy 1

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PERSPECTIVES IN TECHNOLOGY

Solar Energy 1 **Vol.1**

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Perspectives in Technology is a manual produced by the Karnataka State Council for Science & Technology for the faculty and students of engineering colleges of Karnataka. Each issue shall concentrate on one sector of engineering. Copies of Perspectives in Technology, can be acquired by writing to the Secretary, KSCST, Bangalore-560 012.

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Editorial

The Karnataka State Council for Science and Technology (KSCST), was set up in 1975. It was formed as a result of the desire of ministers and government officials on one side and scientists and engineers on the other to work together for the application of science and technology to the problems of eradicating poverty, removing backwardness and spreading development in Karnataka.

KSCST is an autonomous organization. It is a registered society receiving a grant-in-aid from the Government of Karnataka. Since the past few years, it has also received grants from the Department of Science and Technology, Government of India.

During the first few years of its functioning, KSCST's projects were all undertaken by major institutions such as the Central Food and Technological Research Institute, the Indian Institute of Science, the National Aeronautical Laboratory and the University of Agricultural Sciences. Aware of this concentration of projects in a limited number of institutions in Bangalore and Mysore, KSCST was searching for a way of involving the large number of other institutions spread throughout the State.

It was in the this context that a chance visit in 1977 to the engineering colleges of Mysore revealed a mechanism for tapping their enormous wealth of talent. The Final Year BE students of these institutions are obliged to carry out project work as a part of their curricular requirements. But, this project work was handicapped in two ways : (1) shortage of funds, and (2) lack of meaningful topics. Consequently, most of the students tended to concentrate only on "paper studies" or "software problems". All that KSCST needed to do was to provide full financial support and some guidance so

that the student projects could be channelled into areas relevant to the State's interests. This was how the Student Projects Programme (SPP) of KSCST originated in the academic year 1977–78.

The SPP enabled KSCST to break out of Bangalore and Mysore, and reach nine other towns, viz., Tumkur, Davangere, Gulbarga, Bagalkot, Hubli, Manipal, Surathkal, Hassan and Mandya. It also permitted KSCST to utilise the tremendous talent and potential of the students and faculty of the engineering colleges for the benefit of the State.

The SPP has now entered its sixth year of operation. On an average, KSCST has been funding about 150 projects a year at the rate of about Rs. 2,250 per project involving about 15 engineering colleges and an average total expenditure of about Rs. 3.5 lakhs per year of which as much as 88% is spent by the students in colleges on the projects. An average of about 810 students and faculty work every year on the projects.

SPP projects have covered many sectors including: Industry, Energy, Education, Agriculture, Water and Irrigation, Health and Nutrition, Housing, and Ecology and Environment. However, the bulk of the projects have been in the Industry and Energy sectors - in fact 35.57% and 20.03% respectively–and only 10.57% of the projects have been in the Agriculture sector.

Prior to the initiation of the SPP in 1977-78, there were virtually no student projects with a direct relevance to the rural areas of the State, even though 71.6% of its population lives there. To correct what could only be construed as a bias against work of rural relevance, KSCST actively promoted, in the first instance, projects with a potential for application in villages. The result was that initially only about 15% of the projects in the SPP had urban relevance. But, this percentage has been increasing from year to year, and last year about 30% of the projects in the SPP were relevant to

Karnataka's towns and cities. Nevertheless, there is an impression that the SPP is only for projects with a rural bias. Hence, this opporunity is taken to stress that **the SPP is meant to support any student project of relevance to the State, irrespective of whether this applicability is to the rural or urban areas; the SPP is not restricted to rural projects.** This perspective is derived from the viewpoint that only the balanced development of both rural and urban areas leads to the total development of the State.

The SPP has many achievements to its credit. It has stimulated a large number of students and faculty to think of the problems of their immediate sorroundings and to use their knowledge and training to improve this environment. Through involvement with live situations and real problems, the SPP has created an excitement and a challange which has contributed to accelerated learning and an enhancement of the quality of education.

The SPP depends for its success on the availability of high-calibre resources persons. To secure the commitment of such persons it is essential that on the one hand the faculty of the engineering colleges have access to the facilities and experts of institutions of advanced learning and on the other hand the scientists and engineers of the better endowed institutions involve themselves with, and assist, undergraduate institutions.

The SPP has attracted the support of a number of faculty from the Indian Institute of Science, in particular from ASTRA, its Centre for the Application of Science and Technology to Rural Areas. Thus, the SPP has already forged linkages between the Institute and the engineering colleges which are of enormous mutual benefit. Despite this, one of the major problems confronting the SPP is the inadequacy of high-quality resource persons who can devote greater time than is the case now. The interactive bonds between undergraduate and post–

graduate institutions must be strengthened.

Another problem faced by the SPP is the insufficiency, and even absence, of information, analysis and review which will help the participating students and faculty, and in fact the programme as a whole to learn from its experience, i.e., from its successes and failures. After five years of the SPP, over 750 project reports had accumulated in the KSCST library but there was no simple way in which students and faculty could learn from that repository of previous experience and that record of past work. It was not easy to find out what previous batches of students had done, what ground had been covered, what mistakes to avoid, and what challenges need to be addressed. The result: "the wheel was being re-invented" in too many projects.

All this unnecessary duplication is avoided in science and engineering through journals, magazines, seminars and conferences. In short, it is effective communication between the participants which facilitates the collective learning from experience.

If, therefore, the SPP is to transform itself from being a mere collections of disconnected projects into a professional movement which grows by a learning process, a communication system must be established between resource persons, faculty and past and present students.

This newsletter is the first step in that communication process. Topic by topic, area by area, and sector by sector, the newsletter will deal with the fundamentals and the state-of-the-art of the technology, a review of the SPP projects in the field, and a statement regarding what needs to be done. It will permit contact through articles and questions and answers between students and faculty in undergraduate institu-

tions and researchers in post-graduate institutions. Hopefully, it will increase the band of resource persons available to the SPP. Above all, it is intended to make students feel that when they undertake a project they are backed by a great deal of knowledge and a vast team of experts.

—Prof. Amulya Kumar N. Reddy

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Foreword

The term "Solar Energy" conjures different visions for different people. To the optimist it promises a utopian future, capable of transforming poor, energy starved countries into affluent ones. For the pessimist, solar energy, is another in the long list of promises, that will either never materialise, or do so in some remote future. As often happens, reality lies somewhere between these two scenarios.

The advantages of solar energy are obvious – it is available free of cost, it is plentiful, perennial and is not subject to controls; it is a high grade resource, since the thermodynamic temperature of the source is high (6000°K); it is possible to convert it into most other forms of energy : heat, mechanical, chemical or electrical energy. Inspite of these advantages, and the fact that this resource has been available to man all along, it is still a long way away from being utilised commonly, save for traditional uses - such as the drying of agricultural produce and clothing, manufacture of salt, etc. The drawbacks of solar energy are equally obvious : the energy density is rather low being of the order of 6 kWh / m^2 / day and the peak power availability is under 1 kW/m^2. This necessitates availability of large areas over which the energy is to be harvested; the diurnal and seasonal fluctuations make solar energy available for a fixed duration only. If a continuous need arises, then additional storage devices and/or standby sources of other kinds of energy are required. Any technological solar energy application (as opposed to a natural use) is at present very expensive in comparison with conventional energy based applications.

Only in the last seven or eight years have serious efforts been made towards making solar energy a viable and large scale resource. Like every other technology solar technology also

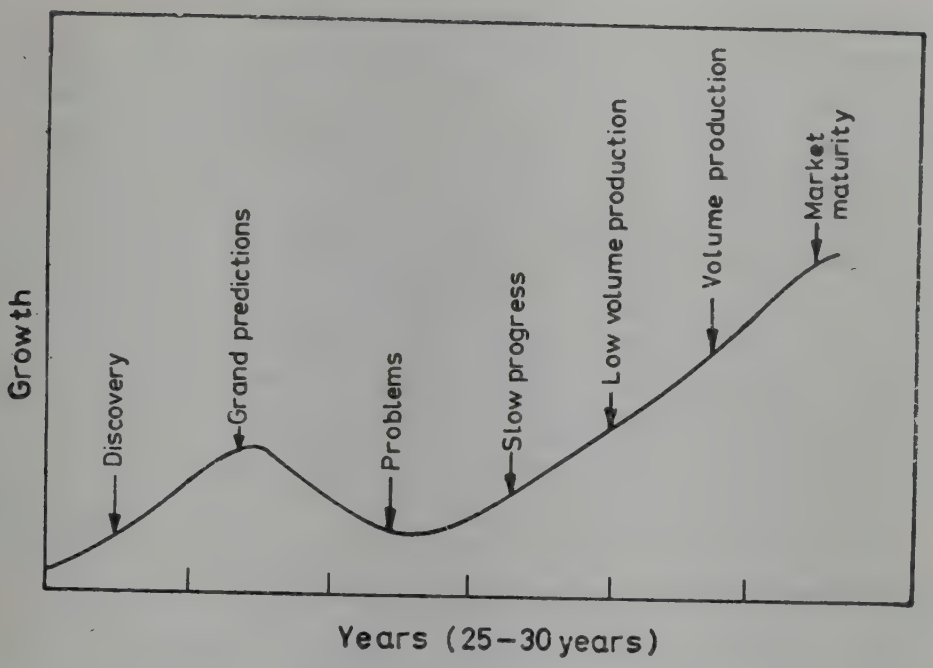


Fig. 1. *Learning Curve*

has to go through different phases of the 'learning curve' (see figure 1).

The rediscovery of the solar option followed the escalation of oil prices. Grand predictions were made about the rediscovered option of solar energy. However, many problems have to be overcome before a technology comes of age. These are identified only later and serious research and development work follows. We are now in this phase.

The first two issues of 'Perspectives in Technology' are being devoted to solar energy and its applications. We hope to acquaint the readers with the prospects and problems of solar energy, and to give a fairly detailed background of the approaches taken in the design, development and analysis of solar energy devices. For convenience the subject of solar energy devices has been divided into two parts, one dealing with active and the other with passive devices. Active devices are those wherein there are moving parts or components like

motors, pumps etc., while passive devices are those which do not depend on such components. The first issue is concerned primarily with flat-plate collectors while the second issue will be devoted to photovoltaic devices, passive air conditioning, concentrators etc.

The first article provides an overview of the entire field of solar energy and solar energy devices. The second and third articles examine the major solar applications of flat–plate collectors in greater depth, describing not only the working of the devices but also pointing out their problems and shortcomings. Simple rules of thumb have been provided for designing these appliances. It is our wish that these articles will serve to provoke the readers, to ask more questions and come up with new problems and innovative solutions.

We hope that the Forum Section of the next issue will contain active contributions from the readers by way of comments and/or questions.

--Prof. C. R. PRASAD

Prof. C. R. PRASAD, is with the Department of Mechanical Engineering, Indian Institute of Science, Bangalore-560 012

1. An Introduction To Solar Energy And Solar Energy Devices

The sun is responsible, with exception, for every kind of energy on earth and has long merited the various forms of worship accorded to it by everyone from ancient Egyptians to modern holiday – makers. Geothermal energy, which comes from the radioactive decay of crustal elements, probably manufactured in long exploded supernovae or other stars, is strictly speaking, alone in being non-solar in origin.

Although a determined pedant could well argue that everything from hydropower through biomass to tar sands, involves solar energy in its creation; in modern energy parlance 'solar' has come to have a comparatively restricted meaning, associated with the direct capture of either the sun's heat or its light.

Even in its restricted definition, solar energy commands devotion from a very wide range of modern mind-sets. These vary from those engineers who believe in the most expensive and advanced concentrations of technology as exemplified by the solar satellite which might beam microwave energy to earth from outer space, to what might be called the soft–energy path devotees who look to a cheap solar cell array on every rooftop to give decentralised energy independence to every citizen who can make a once – in – a – lifetime down payment.

A strict classification of the various forms of direct solar energy would include living plants and photo-chemical devices along with more familiar flat–plate collectors and solar cells. The exploitation of sunlight collected by living plants is an enormous subject. However, it is worth taking

a brief look at the chemical capture of sunlight (i.e. photolysis) since it has attracted the attention of some of the world's most distinguished scientists – Nobel Prize winners Sir George Porter and Professor Melvin Calvin among them. Using the natural catalyst chlorophyll and certain enzymes, water can be split by light into hydrogen and oxygen. Two attractions of the process are immediately obvious - the raw material, water is widely available and the fuel, hydrogen, is non – polluting. Unfortunately, the process has a long way to go before continuous large-scale operations can be evaluated. Indeed, so far the process has been observed only in the laboratory for periods of several hours. Photolysis lies in the distant future but it is clear that the passive use of the sun's thermal energy started in the distant past.

Passive solar heating of the kind achieved in green houses or houses fitted with passive devices like Trombe walls*, etc., is a low – quality energy utilisation, and its use–fulness is restricted. In contrast, electricity can be described as high – quality energy in the sense that it can be used for anything from running computers and radar sets to space heating. The need to match the quality of energy to the end use is well recognised. Thus it is particularly outrageous to use nuclear power stations to provide electricity for night storage radiators when a sheet of glass, a pot of black paint, an existing wall and a minimum of ducting comprising a passive solar heater, will do the job equally well.

Only a third of commercial and residential energy demand has to be satisfied by electricity. At least two thirds of this demand could be satisfied by low – quality solar energy. None of this is to be taken as suggesting that the sun's energy is restricted only to low-quality energy. Far from it. Depen-

* See glossary for explanation of terms.

ding on how it is used, sunshine can provide the highest-quality energy one could wish for. In solar furnaces, focussed concentrated sunlight can produce temperatures as high as 3000°C – more than enough to melt or even vaporise the most refractory materials used by man. It is this potential of solar energy to span the entire range of end-uses that makes it so attractive to energy researchers and innovators. Even capturing thermal energy from the sun can lead to the production of high-quality energy. Trombe walls, green houses and solar water heaters are obvious examples of low-temperature applications. But with modest ingenuity even these comparatively low temperatures can be exploited to produce electricity indirectly.

1.1 POWER FROM THE SUN

Forecasts that solar energy will supply all man's needs by the end of the century, ignore the expensive and undeveloped nature of most solar technologies. The solar radiation falling on the Earth, is about 170 trillion kilowatts (170×10^{12}kW). This is equivalent to 40,000 one kW electric heaters for every man, woman and child on the planet. Yet the world's solar collectors at present yield the energy equivalent of around 400,000 tonnes of oil a year – only one ten thousandth of our present oil consumption.

Some solar technologies are wildly impractical. For example, there are solar cookers which will cook a meal only in bright sunlight, at noon. Others, like solar water heaters and solar ponds – work extermely well, during periods of sunshine.

Harnessing solar energy is impeded by two basic difficulties : the diffuse and variable nature of sunlight. Even in clear tropical regions, solar energy is extremely dilute. It rarely exceeds an intensity of one kilowatt per square metre, and

TABLE 1.1 A PROPOSED LONG TERM SOLAR ENERGY ECONOMY

Demand Sector	End-use energy form	Application	Percentage of overall energy use	Appropriate energy supply technology
Residential and Commercial	Low - temperature thermal energy (<100° C)	Space heating, water heating, air–conditioning	∽ 20–25	Passive and active solar systems, district heating systems
	Intermediate temperature thermal energy (100–300° C)	Cooking and drying	∽5	Active solar heating with concentrating solar collectors
	Hydrogen, LPG, Kerosene, Charcoal, fire wood, coal etc.			Solar thermal, thermochemical or electorlytic generation
	Methane, Biogas			Biomass
	Electricity	Lighting, appliances refrigeration	∽10	Photovoltaic, wind solar thermal, total energy systems
		Subtotal	∽35	

	Intermediate temperature thermal energy (<300° C)	Industrial and agricultural process heat and steam	≈ 7.5	Active solar heating with flat-plate collectors and tracking solar concentrator
	High temperature thermal energy (>300° C)	Industrial process heat and steam	≈17.5	Tracking concentrating solar collector systems
Industrial	Hydrogen, Coal, Petroleum distillates, residuals, etc.			Solar thermal, thermochemical or electrolytic generation
	Electricity	Cogeneration : electric drive, electrolytic & electrochemical processes	≈10	Solar thermal, photovoltaic, cogeneration, wind systems
	Feedstocks	Supply carbon sources to chemical industries	≈5	Biomass residues and wastes or plantations
		Subtotal	≈40	

Demand Sector	End-use energy form	Application	Percentage of overall energy use	Appropriate energy supply technology
	Electricity	Electric vehicles, electric rail		Photovoltaic, wind and solar thermal–electric
Transportation	Hydrogen, Producer gas, Biogas etc., & Coal	Aircraft fuel, land and water transportation vehicles	≈10–20	Solar thermal, thermochemical or electorolytic generation
	Liquid fuels, Methanol, Ethanol, Gasoline	Long distance land and water transportaion vehicles	≈5–15	Biomass residues & wastes or plantations
		Subtotal	≈25	
		TOTAL	100	

under cloudy conditions or in higher latitudes, the energy per square metre is a small fraction of this. Solar radiation is variable. It is zero from dusk to dawn, and is at its maximum in the middle hours of the day. It varies seasonally – in the tropics this variation is small, but in the polar regions it drops to zero for months on end. Unfortunately, man's need for energy tends to be high at night and in winter, when solar energy is least available. The economics of solar power would be revolutionised by cheap, effective storage systems, which allow energy to be put on, from day into the night, and from summer to winter.

Solar energy may be collected and used in two ways : directly, or through biomass, by allowing plants to capture sunlight through photosynthesis, and then burning or otherwise using plant products. Direct solar technologies : solar architecture, solar cookers, solar furnaces, desalination plants, solar ponds, solar water pumps, and photovoltaics will be examined here.

1.2. DIRECT SOLAR TECHNOLOGIES

1.2.1. Energy Architecture

Solar architecture means adapting building methods so as to use as much 'free' energy from the sun as possible. The idea is hardly new. In ancient Greece, houses were built south – facing, with very restricted openings on the north side. South – facing porticos caught the low winter sun, but projecting eaves protected the inhabitants from too much solar energy when the summer sun was high in the sky. Access to sunlight was a political right. The thick adobe walls and earth floors absorbed heat on hot days, and released it at night when the temperature dropped. The main techniques of passive solar heating are still essentially the same, although, the invention of sheet glass and the discovery of the 'greenhouse effect' opened up new possibilities.

A modern example of the exploitation of this effect is the Trombe Wall, (see fig. 1.1) named after Felix Trombe, the French solar energy engineer. A Trombe Wall faces south and is painted black. A sheet of glass is fixed to the wall, leaving a small gap. Sunlight passes through the glass window and is absorbed by the black surface of the masonry, thus raising the temperature of the whole wall. The radiation from the wall is of such a long wavelength that it cannot pass out through the glass. The air in contact with the wall becomes hot and is allowed to escape through slots at the top of the wall into the building of which the Trombe Wall is a part. Cold air is fed in through slots at the bottom of the wall, either from inside the house or from the outside air. The wall is also a warm surface radiating into the house after the sun has set. The economics of the Trombe Wall system are attractive. The technique is suitable for retrofit to existing houses.

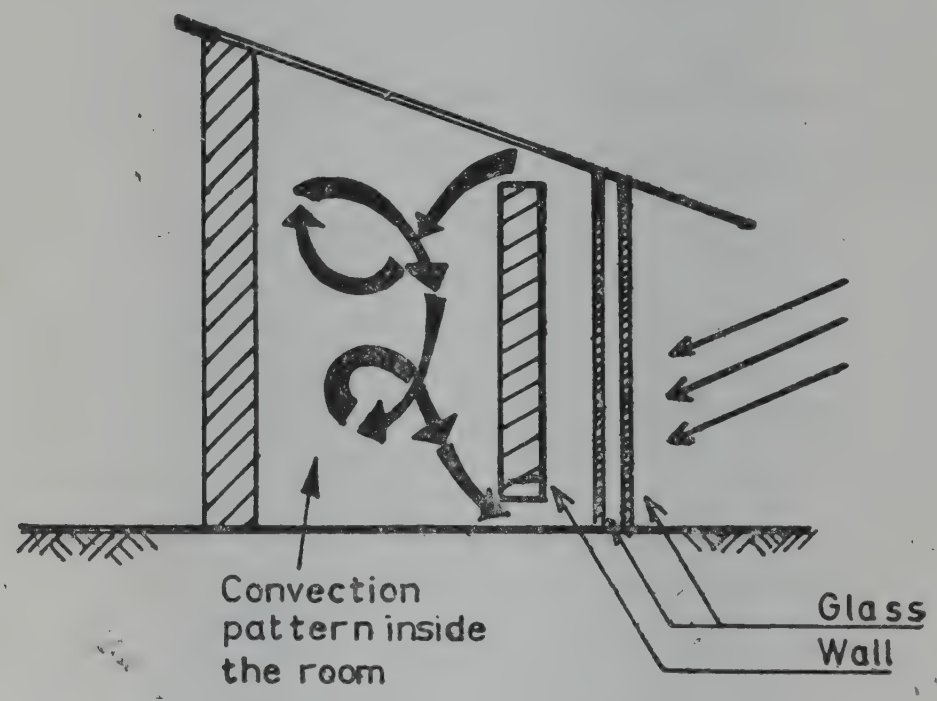


Fig. 1.1 The Trombe wall

The main principles of passive heating are :

1. High standards of insulation.
2. Minimum area of glazed (glass-fitted) windows facing north, and maximum facing south, with windows double-glazed and/or shuttered to keep in heat at night.
3. South-facing conservatories or greenhouses attached to buildings, to trap heat which can then be used to warm the building.
4. Massive, south–facing walls which act as heat sinks, taking in heat during the day and releasing it at night.

Research in the developed countries has demonstrated that good insulation and draught sealing combined with appropriate solar architecture has drastically cut energy consumption when compared with that of conventional buildings. In developing countries, in the Arab world, Latin America, Africa and Asia, traditional architecture and traditional building materials such as brick, adobe, mud, plaster and grass thatch, have the ability to absorb and store solar energy. These have in recent years been almost entirely replaced by Western–style architecture, based on concrete, corrugated iron, glass and steel. Consequently there has been a growing demand for energy, to cool and heat these new buildings.

1.2.2. Active Solar Collectors

Active solar thermal systems use a liquid or a gas to transfer heat from where it is absorbed by a collector to the point of use. There are three basic types : flat-plate collectors, evacuated tubes, and tracking collectors. Nearly all solar collectors are of the flat–plate type. They consist of an absorber panel, a glass or plastic cover in front to let in the heat, insulation at the back to prevent heat loss, and a heat store.

Inside the absorber panel, a heat transfer medium usually water, but occasionally a fluid, air or another gas–carries away the heat to the heat store.

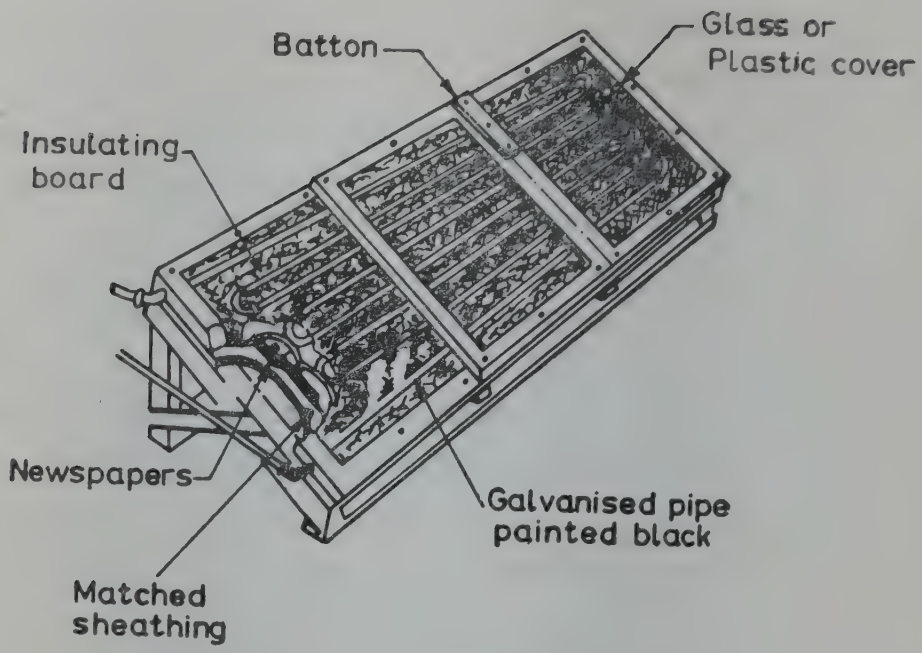


Fig. 1. 2. Flat-Plate Collector

Most solar collectors are mounted on the roofs of houses and use water to transfer heat to a large water tank from which it can be drawn off to radiators or used for the purpose of bathing. Other collectors use air to heat a bed of pebbles or rocks in the basement of buildings.

Solar collectors are simple to construct in theory, but require careful plumbing. They have to be tough to withstand continuous expansion and contraction, and the glass panels must be kept clean if the maximum quantity of solar heat is to be absorbed.

Flat-plate collectors collect direct, (see fig. 1.2) diffuse and reflected solar radiation. Typically they capture 40–60 percent of the energy which falls on them, heating water to 40–30° C. It is possible to reach temperatures of 100–150° C with special absorbent coatings and double or triple glazing. But they are very expensive. Some 7 million square metres of solar collectors are in use today. The cost of a domestic

solar flat-plate collector, including a storage tank, plumbing and fittings, ranges from Rs. 1500 to 4000 per square metre.

Evacuated-tube collectors use a vacuum to insulate it from losing heat. The collector is inside an evacuated tube, with liquid filled pipes to take away the absorbed heat. Evacuated tubes are highly efficient for the collection of direct (and in some designs diffuse) sunlight, and can heat the heat transfer liquid to 150° C. But at lower temperatures, their efficiency is less than a flat-plate collector's. Besides, their costs are several times higher.

Concentrating reflectors, use mirrors or lenses to focus the sun's rays onto a small absorber area. They normally use a tracking mechanism, which can turn the reflector directly towards the sun. So, they must be automatically or manually adjusted, often from hour to hour. Concentrating reflectors can usually absorb direct sunlight when there is a clear sky, while flat-plate collectors can function even on a cloudy day. Some elaborate concentrating collectors can gather both direct and diffuse solar radiation without tracking the sun. One, for example, has two compound parabolic mirrors combined with an evacuated tube. The entire mirror is not in focus at any given moment, and radiation can be gathered from many directions.

The parabolic reflector (see fig. 1.3) has long been used in astronomical telescopes to focus distant parallel rays from a star to a point. Similarly, a trough shaped reflector with a parabolic cross-section will focus sunlight on a line where a water pipe or heat pipe may be placed, to carry away the intense heat. The pipe may be insulated to cut down heat losses, though the insulation must be transparent to sunlight.

Concentrating collectors which focus solar heat along a line can reach temperatures of over 300° C. Higher temperatures, of upto 4000° C are possible using parabolic reflectors, or a series of plane mirrors (heliostats, which combine to

reflect and focus sunlight to a single point). These devices are very expensive, and are likely to be used to generate electricity, as in the solar furnace at Odeillo in the French Pyrenees.

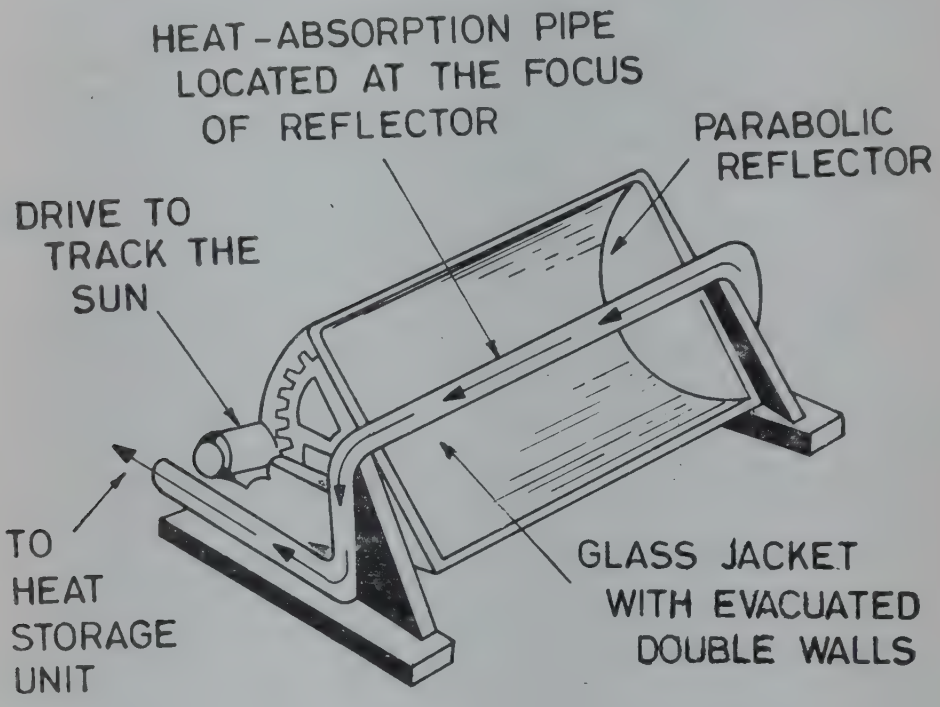

HEAT-ABSORPTION PIPE LOCATED AT THE FOCUS OF REFLECTOR
PARABOLIC REFLECTOR
DRIVE TO TRACK THE SUN
TO HEAT STORAGE UNIT
GLASS JACKET WITH EVACUATED DOUBLE WALLS

Fig. 1.3 Parabolic Reflector

1.2.3. Storage

Most active and passive solar collectors absorb heat at relatively low temperatures, which is mostly used for space and water heating. Since the sun is brightest during the summer day, there is a mismatch between supply and demand. Hence, some form of storage is usually necessary. Storage can be short–term, to last through the night or a few cloudy days, or interseasonal when heat from the summer sun is stored for the winter. Since the problem is to store relatively large quantities of heat at low temperatures, practical storage systems must be both large and cheap.

The simplest systems store the energy as hot water, or in hot pebbles in an insulated tank.

1. A few hundred litres are adequate to cope with most daily fluctuations in a domestic hot water system.
2. Interseasonal storage for space heating in a house may need 1,000 cubic metres of water or more.
3. Rock storage needs 3 – 4 times as large a volume of water, i.e. about 3 – 4,000 cubic metres

More complex storage systems have been developed. Many use mineral salts or paraffin waxes which liquify at low temperatures. The latent heat of phase change (the heat for example that ice absorbs while it melts) gives a potential energy density several times that of water.

1.2.4. Solar Cookers

A number of attempts have been made to construct solar cookers. Some have been more or less successful technically, but none have found practical application.

The usual design is an approximately parabolic dish 1 – 2 metres in diameter. The cooking vessel is placed at the focus and the meal is cooked by sunlight.

In practice the process is slow, cannot be easily controlled, and the dish needs constant adjustment to keep it pointed towards the sun. These devices are awkward to use, blow over in the wind, and can cause severe burns to the cook when the pot is removed or put in place. They require technical skills for manufacture and maintenance which are not readily available in areas where solar cookers would be of most use. The real problem, though, is that solar cookers work well only on sunny days, away from the shade, and around the middle of the day. In most parts of the world, food is cooked in the evening and sensible people stay in the shade at midday. Until some simple way is found, of storing solar heat from midday till sunset and then releasing this heat so that it can rapidly cook a meal, solar cookers will not be widely used.

1.2.5. **Solar Stills**

The sun's heat has been used for over a 100 years to desalinate drinking water. Shallow trays are filled with salt water, their bottoms are blackened, and a sloping sheet of glass is placed on top. The sun's heat is trapped under the glass as in a greenhouse, and evaporates some of the water. This condenses on the glass, runs down and is collected in a trough. The salt remains in the tray ; the evaporated and recondensed water is pure.

Each square metre of still produces 3 – 5 litres per day, costs are high : Rs. 100 – 250 per thousand litres. Solar stills may be cheaper than flash distillation or reverse osmosis for small desalination plants, below 200,000 litres per day capactiy, and at a cost of Rs. 100 – 250 per thousand litres.

1.2.6. **Solar ponds**

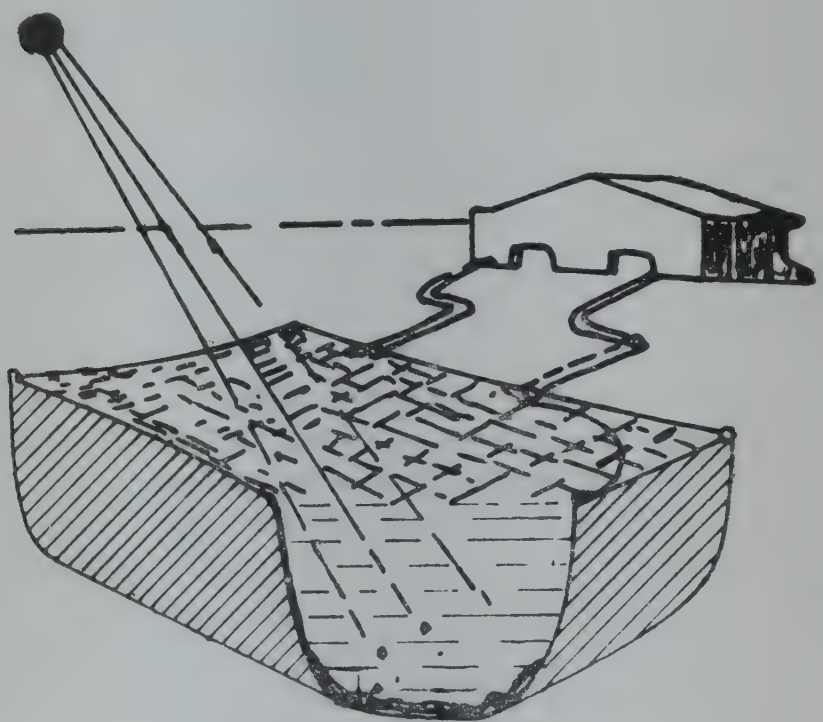


Fig 1.4 Solar Pond

Solar ponds are open-air solar collectors filled with salt water (see fig. 1.4). The bed of the pond is blackened, to absorb solar heat. This heat is then passed onto the water. Normally when the water in a pond is heated by the sun in this way, the hot water at the bottom expands slightly, becomes lighter than the colder water above it, and begins to rise. The convection currents which result, distribute the heat throughout the pond, and some heat is radiated back into the air.

A solar pond has very salty water at the bottom. The bottom layers are therefore more dense than the top, and do not rise even when they get warm. So no convection currents are set up, and the heat is effectively trapped in the bottom layers. The temperatures reached can sometimes approach boiling point. This heat is extracted from the pond by pipes filled with an organic fluid, usually freon, which has a lower boiling point than water, and can be evaporated to drive a turbine to generate electricity. Alternatively, solar ponds can be used for domestic space heating, or to pre-heat water for boilers for industry.

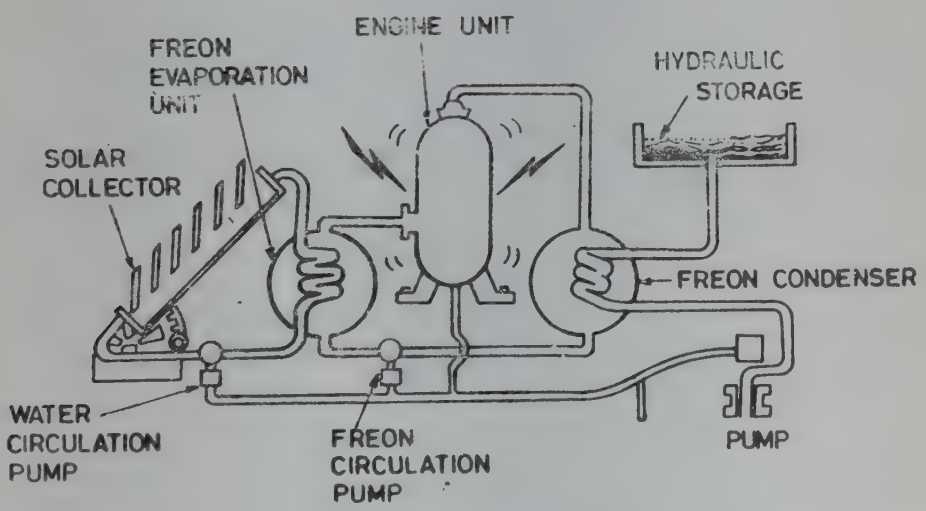


Fig. 1. 5 Solar Engine

A one kilometre square pond gathers energy equivalent to 43,000 tons of oil, and requires about 3 million cubic metres of water annually for surface flushing. But it needs only two people to maintain it, since the plumbing is extremely simple.

The estimated cost of a 5MW Solar Engine is around Rs. 25,000/kW. This price should come down to Rs. 16,000/kW for 40 MW, for larger ponds. Electricity costs should be around 40 to 50 paise/kWh, competitive with other types of generation (see fig. 1.5).

1.2.7. Water Pumps

Solar pumps (see fig. 1.6) can be either thermal–powered (using a collector to drive a low–temperature (freon) turbine)

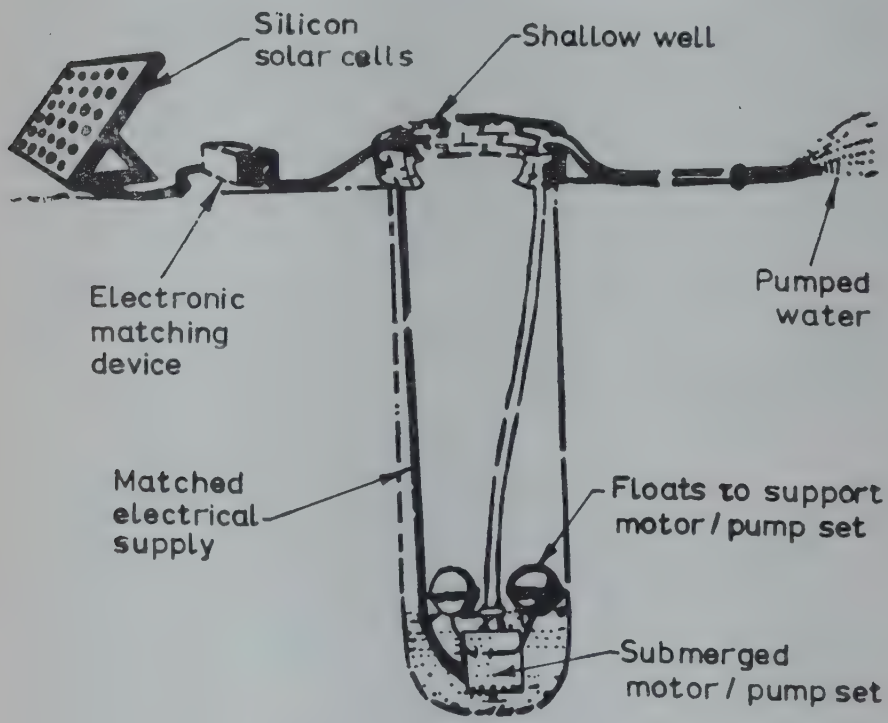


Fig. 1. 6 Solar Pump

or driven by electricity (using a photovoltaic-powered motor). The pumps cost Rs. 48,000 to 65,000 per kW.

1.2.8. Solar Furnaces (STEC)

Solar thermal electric conversion (STEC), loosely known as solar furnaces, operates along lines similar to the generation of electricity from fossil fuel.

A set of mirrors (usually computer–controlled, often called heliostats) tracks the sun, reflecting and concentrating its heat onto a receiver. Normally, the heat boils water, and the steam drives a turbine generator. The mirrors sometimes direct heat to a water boiler on top of a tower; this is often called a solar power tower (see fig. 1.7).

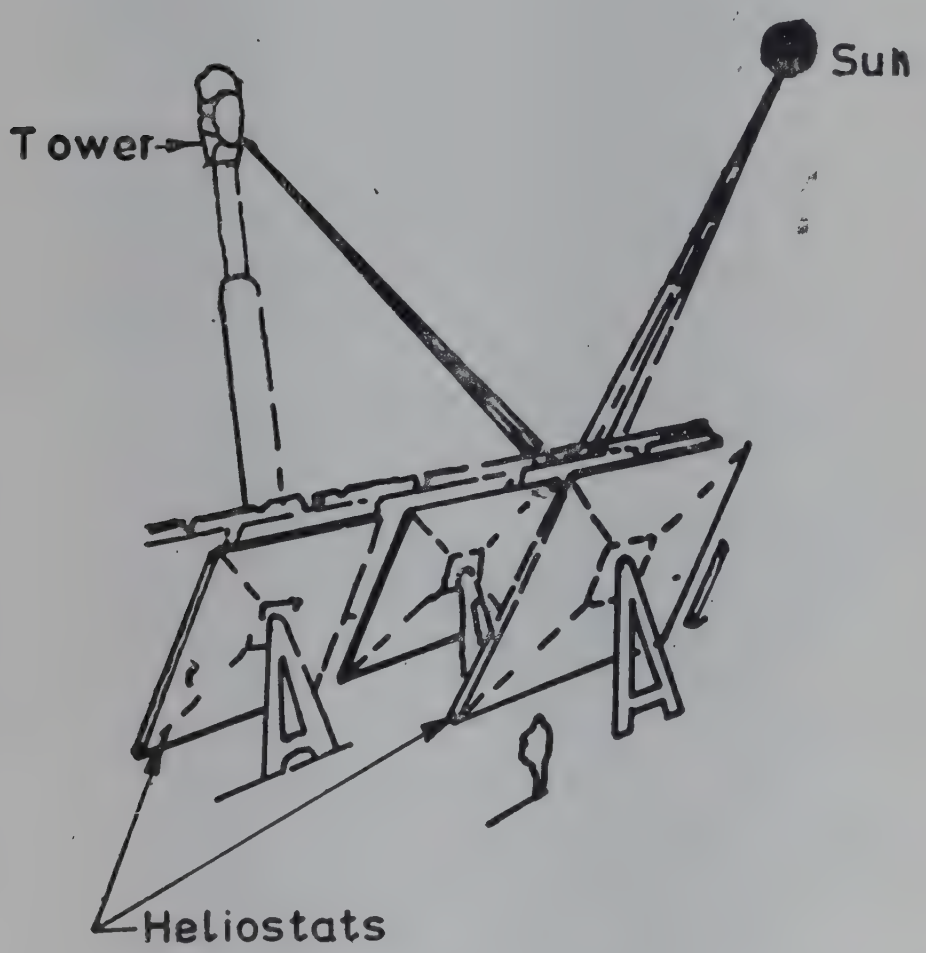


Fig. 1. 7 Solar Power Tower

Units of a few kilowatts might be suitable for pumping water in rural areas. Sizes of 50–500 kW could replace (or assist) diesel generation in remote areas. Other plants of 100 MW and upwards could be used by electric utilities. But the complexity and cost of STEC technology must raise doubts about whether it will be used on any scale at all.

Nearly all the R & D effort on STEC, in the industrialised world is directed towards very large plants (100 MW upwards). Prototype STEC plants of 5–10 MW are scheduled for operation in Japan, the USA and Europe in the 1980s, with commercial plants projected for the 1990s. STEC has only been seriously researched in the last few years, and its technological and economic possibilites are not yet fully known.

Costs of STEC prototypes are naturally very high. The STEC solar furnace represents an attempt to centralise a resource which is by nature decentralised. The technology, still in its infancy, will only survive if costs can be kept down. What is more likely, is that photovoltaic costs will fall dramatically, giving them a decisive edge over STEC for solar electricity.

1.2.9 Photovoltaics

The photovoltaic effect has been known since the 19th century. Einstein received his Nobel Prize largely for explaining it. When light hits certain types of material, it dislodges electrons which flow as an electric current.

Solar cells were first developed in the 1950s by the US Bell Telephone Company. Initially, costs were very high - several thousand US dollars per watt–and their use was largely restricted to satellites. Cost are now falling so rapidly that many authorities feel that photovoltaics will have a dramatic effect on the pattern of electricity generation.

Part of the attraction of photovoltaics, for scientists engaged in research and development, is that they constitute a dramatic example of the "technological fix". The contrast between the solar cell and practically all the other new and renewable forms of energy is very striking. Most of them are comparatively complicated and require constant attention by disciplined, educated people. Even the Trombe wall requires its vents to be closed at night and its glass face to be periodically cleaned.

Other energy forms require intensive labour : Cutting sugarcane, shovelling manure, lubricating and maintaining wind rotors or reworking bore – holes. The solar cell, however, stares at the sky, produces electricity when the sun comes out and stops when the sun goes in. All the difficulties associated with it are to be found in design and manufacture. Once delivered to the consumer, it is a matter of "fit and forget".

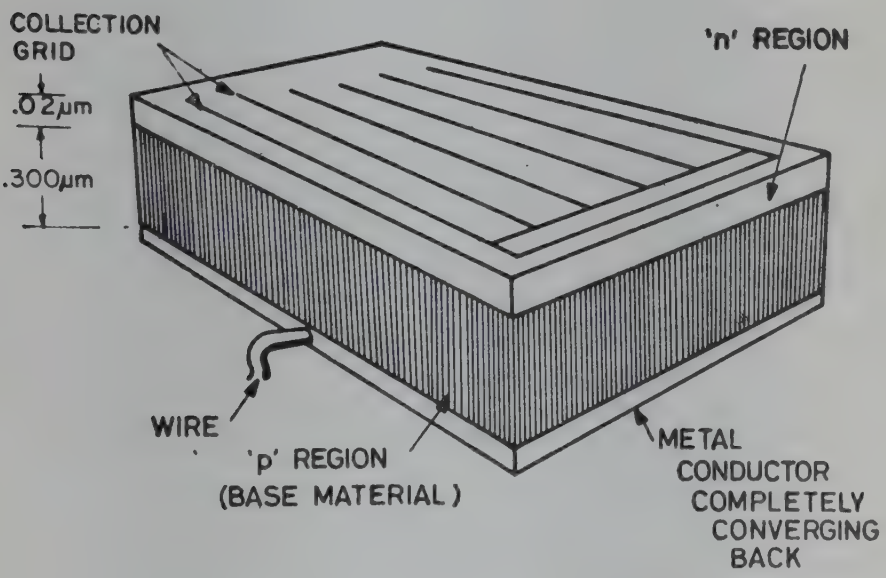


Fig. 1.8 Anatomy af a cell

Intense activity is going on in both the design and manufacture of solar cells. Economic success for a particular kind of

Table 1.2 **Photovoltaic Cell Materials Options**

Type of Solar Cell	Silicon			Gallium Arsenide Ga Al As	Cadmium Sulphide–Cu_2S	Indium Phosphide–CdS	SnO_2 Si & other CdS combinations
	Monocrystal	Polycrystal	Amorphous				
Max. theoretical efficiency %	22	≈ 20	≈ 15	24	12–16	≈ 30	15–30
Typical commercial efficiency %	12–14	6.5	—	12–19	8.5	—	—
Achieved laboratory efficiency %	18	10	5	23	8–12	11–14	10–15
Band Gap eV	1.1	0. 7–1.0	0.6–0.9	1.4–2.2	1.2–2.4	1.3–2.4	
Estimated final cell cost index	100	20	2	500	5	10	

Advantages	Excellent silicon material availability. Established technology		Cost potential	Temp./ concentration properties. Efficiency	Cost Potential	Temp./ concentration properties. Efficiency	
Disadvantages	st	Brittleness restricts area	Efficiency	Material availability Cost	Efficiency Cadmium availability	Material availability	Considerable development needed
				Unknown long term stability properties			

solar cell will depend on a complex trade-off between raw material cost, cost of manufacturing equipment (and its own energy consumption), and the cost of the cell infrastructure.

In practice, most solar cells (see fig. 1.8) are made from semiconduting materials, which are composed of two layers, one or both of which are "doped" or impregnated with a photo-active chemical. Some of the more important types are :

Silicon : Until recently all commercially available solar cells were made from single crystals of high purity silicon. Polycrystaline silicon may prove much cheaper. Another type, amorphous silicon, can easily be fabricated in thin films on a glass or a ceramic base, and promises to be even cheaper.

Cadmium sulphide - copper sulphide : Shows a long term promise and requires only very thin films (under 30 microns) of relatively cheap industrial chemicals.

Gallium arsenide : Has a high efficiency but high cost, and needs to be used with a collector system which directs the sun's rays onto a relatively small area.

A photovoltaic cell is small, typically a few centimetres across. A cell 10 centimetres in diametre will produce about 1 peak watt of electric current at 0.5 volts. A photovoltaic panel is made by assembling a large number of cells together. A number of panels plus voltage controllers, and perhaps DC-AC convertors produce usable electricity.

The efficiency (the proportion of solar energy which is converted to electricity) of a solar cell varies from 5 to 15%; laboratory experiments have reached 25-30%. But in practice these efficiencies are reduced by the difficulties of manufacturing cells of the required purity or cyrstalline structure. It may be cheaper, especially with expensive cell materials,

to increase efficiciency by using a lens or mirror concentrators to focus the sun's rays.

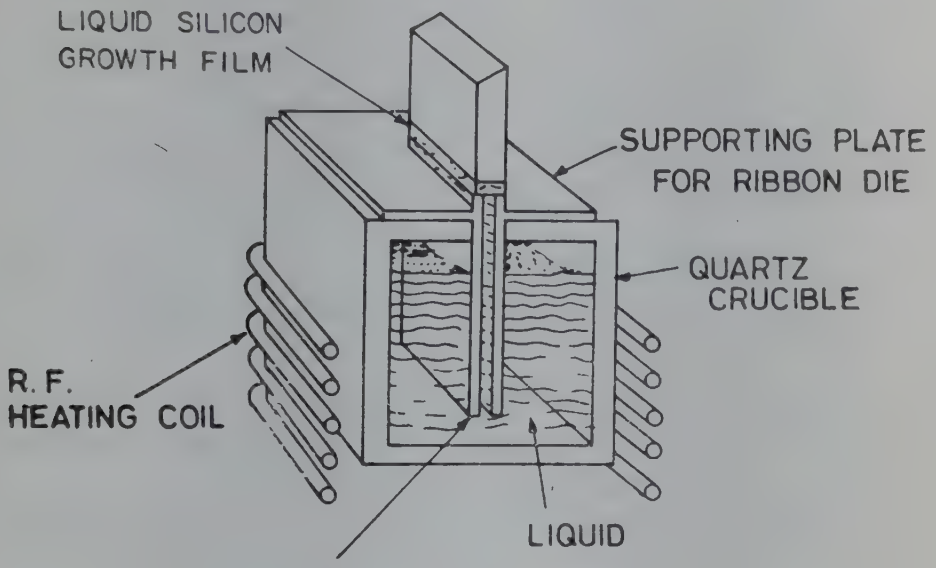


Fig. 1.9 Crystal Growing

Photovoltaic systems operate in direct sunlight, hence, some storage or back–up power is normally required. As the cost of cells falls, the cost of storage as a proportion of total costs is expected to rise, to well over 50% by 1990.

The standard method of producing single crystals (see. fig. 1.9.) of silicon for solar cells is the Czochralski technique : a seed crystal is dipped into molten silicon and slowly withdrawn as it grows. Single crystals over 12 centimetres in diameter have been produced. These are then sawn, with diamond blades, into wafers of 0.2–0.35 mm. thickness. Upto 50% of the silicon is lost as 'kerf' in the slicing process.

The Dendritic web technique, developed by Westinghouse, to reduce kerf losses, uses two parallel needles dipped into supercooled silicon, to pull up a film of silicon between them.

A third technique is called edge–defined film growth (EFG) or capillary action shaping techique (CAST), developed

by Mobil Tyco and other companies. A die is used to present a very thin edge of molten silicon to the seed crystal. This method has the potential of reaching the 1986 goal of 70 US cents per peak watt. Photovoltaics is a fast moving, and highly competitive field in which new developments, are announced frequently. The dramatic reduction in size and cost of pocket calculators over the past decade indicates the achievements of related semi – conductor technology.

Solar cells are ideally suited to power TV sets, telecommunication systems, refrigeration plants, water pumps and small power stations for isolated villages. Even at present costs, the needs of remote rural communities needing less than 5,000 kWh of electricity a year can be met more cheaply by solar cells than by other generating systems. If costs fall to the 1986 US goal of 70 US cents per peak watt, then photovoltaics could be the cheapest source of electricity for all decentralised systems in developing countries.

Photovoltaic programmes in the Third World are dominated by what is happening in the industrialised world. However, most Third World villages have at present very little demand for electricity. Their needs are for cooking meals, lighting homes, pumping water and grinding grain – tasks for which electricity is not always suited because of the high cost of the appliances involved.

Widespread use of photovoltaics will become a possibility if there is a dramatic lowering of costs. Prices for solar cells have already fallen from several thousand dollars a peak watt to under $12/W. The most ambitious targets have been set by the US Department of Energy, which plans to spend $1.5 billion on photovoltaics in the decade 1978–88. The goal is 70 cents per peak watt in 1986, and 15 cents in 1990. This would be barely 1% of the present prices.

Elsewhere in the industrialised world, US projections are regarded as being somewhat optimistic. European costs tend

to be higher than US, partly because production runs are smaller and partly because European companies consider American prices to be subsidised by government funding.

If the US projections turn out to be accurate, photovoltaics have a bright future. They are already competitive for certain specialised functions such as telecommunication relays in isolated areas. At 70 cents/W, solar cells would compete economically with diesel generation, whereas 15 cents/W would make solar panels virtually as cheap as nuclear power or large fossil fuel plants.

But at present this is nowhere near the case. Although photovoltaic running costs are low when compared with other energy sources, capital costs are high. A series of solar cells producing one kilowatt, costs Rs. 1.0 to 2.0 lakhs. A 1kW diesel generator costs Rs. 7,000/–.

1.2.10 Solar Action and Prospects

Despite its supposedly universal and decentralised nature commercial solar technology shows many of the problems of monopoly and nationalism found in other spheres of economic activity.

Most solar funding comes from the governments of industrialised countries. The patten of spending is dictated by a complex mixture of forces : perceived (though not necessarily real) national priorities to replace existing energy sources, technological chauvinism, pressure from industry and from ecological groups, and fear of losing the race for apparently lucrative solar markets. Very low down indeed in the order of priorities are the real needs of the non–oil Third World.

Private enterprise appears to have singled out small-scale decentralised systems as offering the best opportunities. But government agencies continue to sponsor research on

large-scale, centralised projects. The biggest project under construction is the 10MW solar thermal power tower at Barstow in California. The biggest proposed is the $ 100 billion solar power satellite (SPS) system. This would use 50 square kilometres (20 square miles) of solar cells to capture the sun's rays and beam 5,000 MW of energy to Earth as microwave radiation.

The material in this chapter has been extracted from "New and Renewable Energies. 1" and "14. Sources of New and Renewable Energies", published by the Earthscan Publications, London, for the UNERG Conference, Nairobi, August 1981.

2. Radiation from the Sun

An estimate of the amount of solar energy falling on the surface of a solar energy device, whether it be a concentrator mirror or a black absorber surface of a flat-plate collector or a solar cell or the walls of a building that is being heated or cooled, is the first prerequisite before proceeding to either the design or deployment of such devices. Depending on the application, hourly, daily, monthly or annual radiation data, and in some cases even the irradiance contained in certain spectral intervals (for example in the interval from 0.4 to 1.1μ m for silicon solar cells) may be required.

For a crude estimate, the overall annual average solar radiation falling on a horizontal surface over most of India can be taken to lie between 225 and 250 W/m^2, which works out to about 6 kWh/m^2/day of energy. The peak power that can be expected is under 1 kW/m^2.

Such a crude estimate will not suffice in most cases. When necessary one can use the tables of solar radiation data pertaining to India, that have been compiled by the India Meteorological Department [1]* and the Handbooks of Solar Radiation, published recently, by A. Mani [2]. These tabulations give the average monthly mean daily solar irradiance for a horizontal surface for several important stations in India; in addition, maps of expected monthly global and diffuse solar radiation, as well as sun shine hours over India are provided. Hourly solar radiation, sunshine hours, direct and net radiation, long wave radiation, hourly air temper-

* The figures in square brackets indicate the reference number in the Bibiliography, at the end of chapter 3.

ature, relative humidity, wind speed, and rainfall for 18 Indian stations are available [2]. However, such detailed data is not available for all stations in India. Using a limited set of measured metecrological parameters, solar radiation for an additional 127 stations in India have been derived in the second volume of Handbook of Solar Radiation Data for India by A. Mani and S. Rangarajan [2]. In such cases, where solar radiation measurements are not available it is possible to make fairly accurate estimates of the available, solar energy. A few relations which will prove useful for this purpose are given here. Since the distance of the sun from the earth is 149.5 x 10^6 km, and the radius of the sun's disc is 696 x 10^3km, the angle subtended by the sun's disc at the earth is a mere 1/2 degree of arc, with the result that the radiation from the sun can be treated as a narrow beam of radiation from a point source.

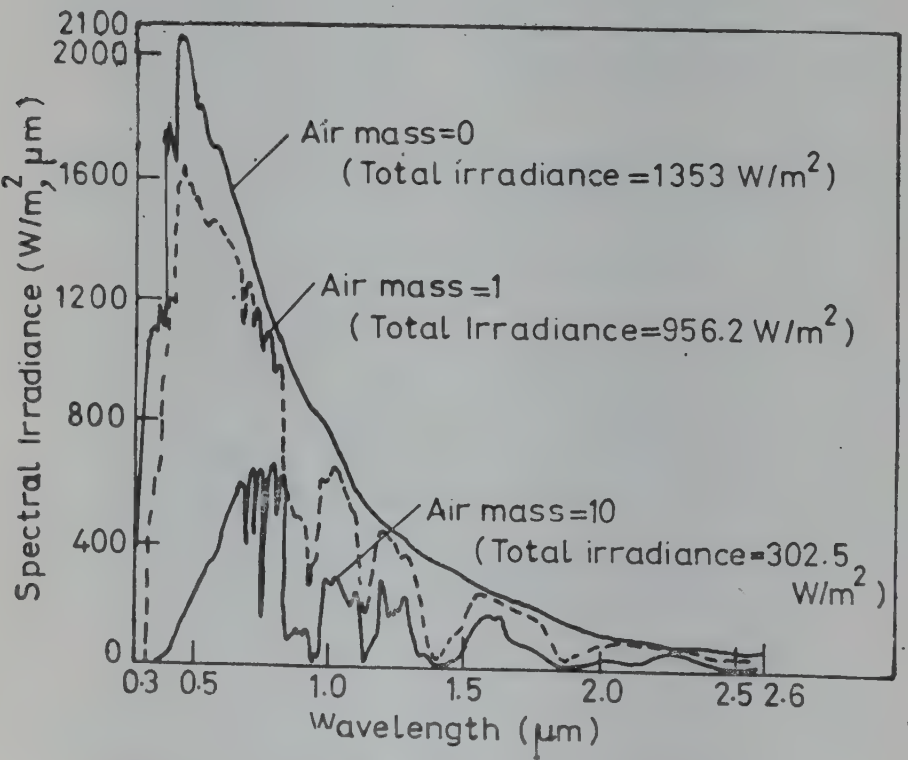


Fig. 2.1. Solar Radiation Spectral Distribution

2.1 Spectral Distribution

For all practical purposes the sun can be treated as a blackbody source whose temperature is 5760°K, so that its spectral distribution* is given by the Planck distribution (see figure 2.1), with its peak lying near 0.5μm and having the bulk of its energy lying within 0.2 to 3μm range. The intensity of radiation falling on a surface normal to the sun's direction, just outside the earth's atmosphere is called the solar constant (I_{sc}), its value is 1353 W/m^2. Table 2.1 gives the fraction of the total radiation falling in different spectral bands [3–5.]

Table 2.1

Spectral Irradiance outside earth's atmosphere

Wave length Range (μm)	Solar irradiance within wave length range (W/m^2)	Percentage of Total
Ultraviolet		
0.115–0.405	125.737	9.293
Visible		
0.405–0.740	561·172	41.476
Infrared		
0.740–2.000	578.000	42.720
2.000–5.000	81.491	6.023
Total		
0.115–1000	1353.000	100%

The radiation reaching the surface of the earth is attenuated by the atmosphere, where it is partly absorbed and scattered. Absorption is primarily effected by the infrared active gaseous species, like CO_2, H_2O and O_3, while scattering in the

* For description of terms and symbols used, see Glossary and Nomenclature.

ultraviolet and visible range is caused by gaseous molecules (Rayleigh scattering). Suspended particulate matter (aerosols) whose concentrations and sizes vary from place to place and in time, cause scattering over the entire spectral range. The spectral distribution of radiation reaching the surface of the earth [5] when the sun is directly overhead, i.e. for air mass m = 1, zenith angle = 0°, is shown in the figure 2.1. Fig. 2.1 also indicates the spectral distribution when the sun makes an angle Z of about 84.3° to the vertical, at which time the beam travels through a path which is ten times longer than the path corresponding to that taken when the sun is directly overhead, i.e. for the air mass m = 10. These results are valid for clear skies. When the sky is turbid, (i.e. when visibility is reduced, due to large concentrations of particulates) the relation given by Angstrom can be used for calculating the attenuation suffered by solar radiation on reaching the ground.

Here the attenuation coefficient C_3 due to turbidity is given by :

$$C_3 = \xi/\lambda^{\psi} \qquad \text{.....(1)}$$

where ψ and ξ are Angstrom coefficients [4] available in tabulated form, and λ is in μ m. By assigning to each of the attenuation processes, like absorption(C_1), Rayleigh scattering (C_2), coefficients, the radiation I_g reaching the ground can be related to the solar constant I_{sc} by

$$I_g = I_{sc}\ T \qquad \text{.....(2)}$$

where $T = \exp\ (-[\Sigma_n\ c_n\ l_n]\ m)$ is the transmittance of the atmosphere. A simple empirical relation for T [4] is

$$T = \{\exp[-0.65\ m\ (A, Z)\ ] + \exp\ (-0.095\ m\ (A, Z)\ \} \times (0.5) \qquad \text{.....(3)}$$

$$m\ (0, Z) = [\ (614 \cos Z)^2 + 1229]^{1/2} - 614 \cos Z \qquad \text{.....(4)}$$

and, $m\ (A, Z) = m\ (0, Z)\ p\ (A)/p\ (0)$

2.2. Beam and diffuse components

A part of the solar radiation is lost to space, during its transit in the atmosphere, by scattering, but, a significant part of the scattered radiation returns to the earth. The radiation striking the earth is then partly reflected by the surface of the earth, and a part of this reflected radiation is scattered again back to the earth. Hence, the radiation reaching the earth consists of the beam component and a diffuse component. The angular distribution of this diffuse radiation is more or less uniform except for a peak along the beam direction. For clear skies the diffuse component depends on the air mass, water vapour and aerosol content of the atmosphere, and is found to vary both geographically and with time. Empirical relations for estimating the diffuse component from the total radiation reaching the ground, are established by carrying out experimental measurements [3, 5, 6,].

2.3. Estimation of Solar Radiation

Since the actual measurement of solar radiation at every location is impractical, an empirical relation (developed originally by Angstrom) commonly used is

$$H = H_o \left(a + b \frac{n}{N}\right) \qquad \text{.....(5)}$$

which relates H, the average total radiation reaching a horizontal surface on the earth to H_o, the extra-terrestrial total radiation (i. e. solar constant) and the ratio of the actual sunshine hours (n) to the maximum possible duration of sunshine hours (N) at a particular location and time. The two constants a and b are empirically derived for the location over a period of time.

In most analyses, hourly values of the beam and diffuse radiation are required. As already stated such measurements are available for a limited number of stations. On the other hand the monthly average of total daily radiation is more

readily available in a tabulated form. For computing the hourly values there are many methods [6, 7] ranging from the classical empirical Liu and Jordan method to the sophisticated computer codes of the NBS – LD programmes. Liu & Jordan defined a new empirical constant $K_t = \bar{H}/H_o$ which was found to be related to the average daily diffuse radiation d as :

$$d/H = \begin{cases} 0.99 \text{ if } K_T \leq 0.17 \\ 1.188 - 2.272K_T + 9.473\,K^2_T - 21.856\,K^3_T + 14.648\,K^{4T} \\ \text{for } 0.17 < K_T < 0.8 \end{cases} \quad \ldots\ldots\ldots\ldots(6)$$

If the monthly average mean daily radiation $\bar{H}$ is available, $\bar{d}$ the monthly average diffuse radiation is correlateted with $\bar{K}_T = \bar{H}/H_o$, the monthly average cloudiness index as :

$$\bar{d}/\bar{H} = 0.775 + 0.347\,(h_s - \pi/_2) - [0.505 + 0.267)\,(h_s - \pi/2)] \times \cos\,[2\bar{K}_T - 0.9)] \ldots\ldots\ldots\ldots(7)$$

This empirical relation was derived from the data obtained for many U.S. stations. Now, the hourly average diffuse and total intensities I_d and I_T can be evaluated from H and d as [7]

$$I_d\,(h, h_s) = \frac{d\pi\,(\cos h - \cos h_s)}{24(\sin h_s - hc_s os\ h_s)} \quad \ldots\ldots\ldots\ldots(8)$$

$$I_T\,(h,\ h_s) = \bar{H}\left\{ \frac{\pi}{24}(a^1 + b\cos h)\ \left[\frac{\cos h - \cos h^s}{\sin h_s - h_s \cos h_s}\right] \right\} \ldots\ldots\ldots(9)$$

with $a_1 = 0.409 + 0.5016 \sin (h_s - 1.041)$

$b_1 = 0.6609 - 0.4767 \sin (h_s - 1.047)$

The beam component of intensity I_b is obtained by taking the difference between I_T and I_d. Depending upon whether meteorological tables are available or not, the appropriate expressions (or similar ones) given above can be used to obtain hourly solar irradiances. But since the solar radiation is directional, the angular location of the sun in the sky should be known as a function of local time as well as the inclination of the surface which is receiving the radiation.

2.4. Direction of Beam Radiation

The zenith angle Z that the sun makes at any time (see fig. 2.2) is

$$\cos Z = \cos L \cos \delta \cos h + \sin L \sin \delta \quad \text{.....(10)}$$

Here the solar declination δ, is given by

$$\delta = (23.45) \sin (360 d_n/365.25) \quad \text{.....(11)}$$

The length of the day D (in hours) and the sunrise (or sunset) hour angle h_s are :

$$D = (2/15) \cos^{-1} (-\tan L \tan \delta) = 2h_s /15 \quad \text{.....(12)}$$

$$h_s = \cos^{-1} (-\tan L \tan \delta) = 2\pi t_s/T \quad \text{.....(13)}$$

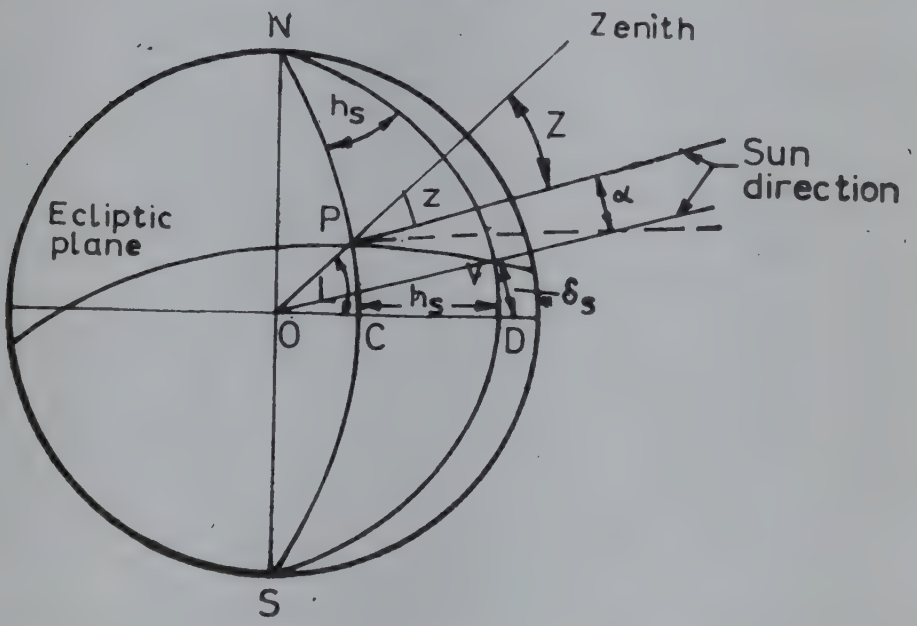


Figure 2.2. Definition of Solar angle h_s (CND), Solar declination δ (VOD) and the Latitude angle L (POC) Solar-altitude angle α at P the Location of interest,

It should be noted that the hour angle refers to the solar time. The local solar time is related to the standard time by

Solar time = standard time + equation of time + 4 (standard time zone meridian – longitude of the place).....(14)

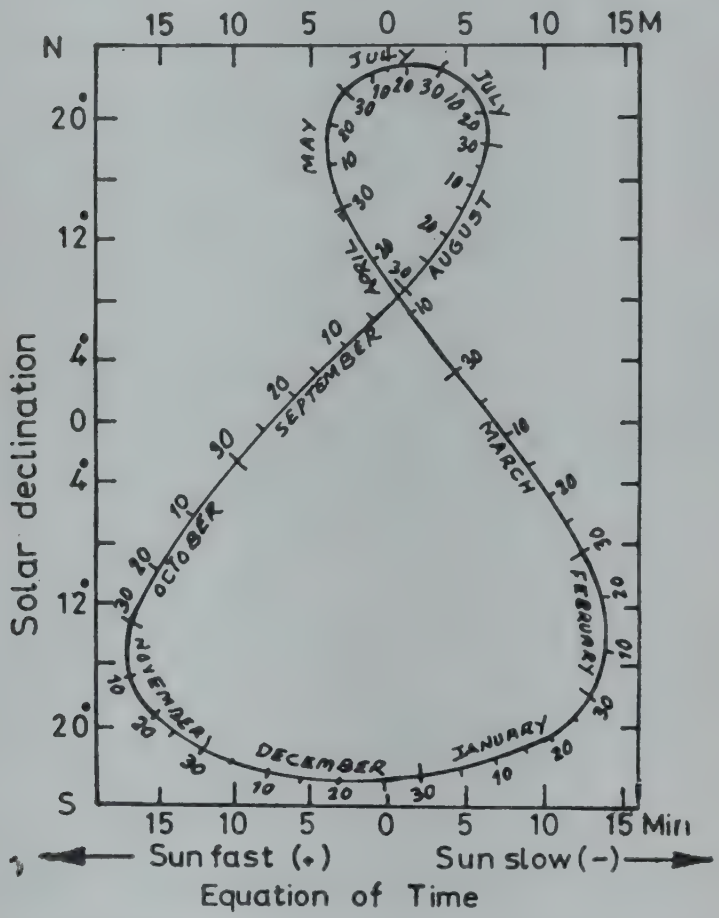
The 'equation of time' can be obtained from the analemma fig. 2.3).

The solar irradiance on any inclined surface (see fig.2.4.) is given by

$I = I_b \cos i + I_d r_d + I_{Th} R_g r_R$ .....(15)

And $\cos i = \cos (a_r - a_w) \sin z \sin \beta + \cos z \cos \beta$ .....(16)

Here $a = \sin^{-1} \left(\frac{\cos \delta \sin h}{\sin z} \right)$ .....(17)



ig. 2.3. The analemma-a graphical presentation of the equation of time.

To simplify matters, the diffuse radiation from the sky may be taken as isotropic, in which case

$r_d = \cos^2 (\beta/2)$ and $r_R = \sin^2 (\beta/2)$ .....(18)

More accurate relations where the anisotropy of diffuse radiation is taken into account are given in the references [3, 4 and 5].

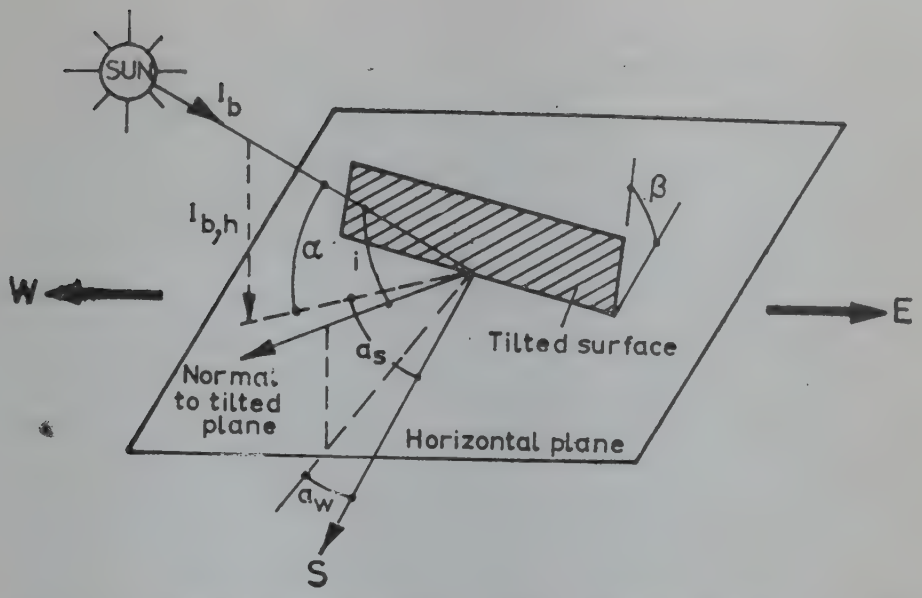


Fig. 2.4. Definition of incidence angle i, surface tilt angle β, Solar altitude angle α, solar azimuth angle a_s, wall azimuth a_w, beam component I_b, component of beam radiation on a horizontal surface $I_{b,h}$

2.5 Instruments For Measuring Radiation

Instruments for measuring the number of sunshine hours in a day, the diffuse, direct and total (or global) solar radiation, its spectral distribution, are in common use all over the world. These instruments have to carry out absolute measurements of radiation and furthermore the measurments have to bear a direct correspondence with all the instruments in use at present and also in the past. Hence, these requirements place very exacting demands on the performance of the instruments, by specifying close tolerances on the variations in sensitivity, long term stability, temperature coefficient, linearity, spectral selectivity, cosine and azimuth response, time constant, etc.

The instruments generally fall into the following classes.

2.5.1. Pyranometer:

Pyranometers are used for measuring the total (global)

radiation received from the upper hemisphere. Its sensor is a small flat surface which is blackened to absorb radiation in all the 2π directions and all wave lengths. Two concentric hemispherical transparent (glass) windows are used as covers for the sensor. The sensor is usually a thermopile, the hot junctions being painted black and exposed to radiation while the cold junctions are shaded or covered so that they do not abosorb any radiation. The surface of the sensor has to accept radiation at all incident angles with equal sensitivity. Pyranometers can also be used to read the diffuse sky radiation, by the simple addition of a "shading ring" which blocks the direct (beam) radiation from reaching the sensor. By orienting the sensor downwards, it is also possible to measure radiation reflected from the ground.

Many commercial instruments are available which are classified as absolute standard, first class, second class and third class. Most of the commonly used devices fall into the second class. These are the Epply, Moll–Gorczynski and other pyranometers. In India, M/s National Instruments Ltd., Jadavpur, Calcutta 700 032 manufacture thermopile based pyranometers.

2.5.2 Pyrheliometer :

The pyrheliometer is used for measuring the direct or beam component of solar radiation, at normal incidence. Basically a collimator with a small field of view (less than 5.7°) oriented along the direction of the sun, directs the beam radiation to a detector (a blackened thermopile element) in a pyrheliometer. The most famous of these are the Angstrom compensation pyrheliometers introduced in 1899 (some of these are still in use) and the Abbot silver disc pyrheliometer introduced in 1902. At present, Linke–Fuessner and Epply pyrheliometers are commonly used for beam measurements. In India, National Instruments Ltd., also make pyrheliometers.

2.5.3. Sunshine recorder

The sunshine recorder is a simple device to measure the duration over which bright sunshine is present. The most common instrument is the Campbell–Stokes recorder, consisting of a 10 cm diameter glass sphere mounted within a spherical bowl so that the beam is focussed sharply onto a card held in a groove on the bowl. Only bright sunshine causes the paper to burn ; so that a burn path, corresponding to the motion of the sun is traced on the paper, for the period when bright sunshine is present. Another commonly used instrument is a photoelectric sunshine recorder, which essentially is a diffetential instrument consisting of two photo–detectors, one shaded from direct radiation, and the other exposed to direct radiation. In the differential mode, the diffuse radiation reaching both the cells are made to oppose each other so as to produce no output. The presence of bright sunshine causes the operation of a relay or recorder, to mark the duration of sunlight, in periods of 1 minute each.

2.5.4. Spectroscopic measurements :

Spectroradiometers consisting of a spectral dispersing unit (monochromator) and detector, can be used for measuring the radiation, in any wave length range of the spectrum. However, these are too sophisticated for field measurements. The simplest method, is to use coloured glass filter hemispheres over the pyranometer, so that the radiation transmitted through these covers is in different spectral bands. For example fused quartz (.250 – 3.500μm band),) soda glass (0.35–2.8μm), Schott glass OG 1 (orange coloured, 0.525–2.800μm), red Rg 2 (.630 – 2.800 μm), KRS 5 (0.6 to 30μm), polyethelene (0. 3 to 50μm), and other similar covers can be utilised for measuring spectral irradiance.

2.5.5. Photovoltaic instruments :

Simple photovoltaic cells, either silicon, cadmium sulfide or germanium which respond to solar radiation, can be used

for solar radiation measurements, albeit, with lesser accuracy. The main problems, are related to their limited (0.4 to 1.1μm for silicon) and non–uniform spectral response, poor stability and strong directional dependence on sensitivity. Inspite of these drawbacks their low cost and simplicity–recommend their use. But if absolute measurements of solar radiation are desired, then the initial calibration, should be followed by a fairly elaborate set of computations, for deriving the desired radiation quantity from the measured output [8, 9]. This is due to the limited and non–uniform spectral response of the solar cells. Central Electronics Ltd., Ghaziabad make photovoltaic meters called "Suryamapi" for measuring relative intensities.

2.6. PROBLEMS, PROSPECTS AND TASKS

There are many interesting and challenging problems that one encounters in the measurment of radiation from the sun. The most evident task would be to generate data for many more geographic locations so that a more complete set of measured values of solar radiation is available. This is, however, by no means an easy or simple task.

Since absolute and not relative measurements are involved here, precision, stability and accuracy of measurements place very exacting constraints. These call for the use of the first or second class of instruments and primary or secondary standards for calibration. These instruments are expensive, the process is time consuming, and will not provide any new insights to students planning to carry out such a project.

On the other hand there are a number of other aspects that need less precise data. Some of them are listed here.

2.6.1. Diffuse radiation : Sufficient data on diffuse adiation is not available. Here the fraction of diffuse radiation in the total is to be found. By carrying out a sufficient

number of measurements, useful empirical relations that pertain to local situations can be found. These would be extremely useful.

2.6.2. The reflectivity of ground (albedo) for different conditions can be determined.

2.6.2. Development of sunshine recorders based on photocells.

2.6.4. Development of simple photo-cell pyranometers and pyrheliometers, and their calibration to yield diffuse and global irradiance.

2.6.5. Development of equitorial mountings for tracking the sun.

2.6.6. Development of a simple calculation procedure to convert the solar cell output into absolute flux.

2.6.7. Development of thick film and/or wire wound thermopiles.

These and many other problems of a similar nature can be tackled. For carrying out calibrations, however, a number of secondary standards of radiation and first and second class pyrano/pyrheliometers that are available at IISc.. and other meterological stations, can be utilised.

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3. Design, Fabrication and Application of Flat-Plate Collectors

Apart from the natural conversion of solar energy, (into heat energy by the oceans and atmosphere, into stored chemical energy by plants via photosynthesis, etc) the most widely adopted technological converter of solar energy, at present, is the flat–plate collector. Basically it is a very simple device-easy to construct and operate.

These collectors consist of a flat or corrugated surface with a black coating, for absorbing solar radiation and converting it to heat. This heat is then transferred to a working fluid, generally water or air, by the use of ducts attached to the plate, through which the fluid is circulated. The highest temperature that such a device can attain, depends not only on the input radiation intensity, but also on the losses suffered by the collector by way of re-radiation, convection as well as conduction. The effectiveness of the collector then depends on how well these losses are reduced.

A simple illustration is given below to highlight the importance of reducing these losses. Consider a flat blackened surface lying horizontal on the ground. A simple energy balance [4] expression can be written as :*

$$\tau \alpha_s A_c I = A_c h_w (T_p - T_a) + \epsilon_p \sigma A_c (T^4_p - T_{a,}{}^4_r) + q_u + q_s + q_{lc} \ldots (1)$$

This energy balance helps us to understand the basic criteria in designing a flat-plate collector. The aim in the design of any collector is to extract as much of the incident

* (For description of terms and symbols used see Glossary & Nomenclature).

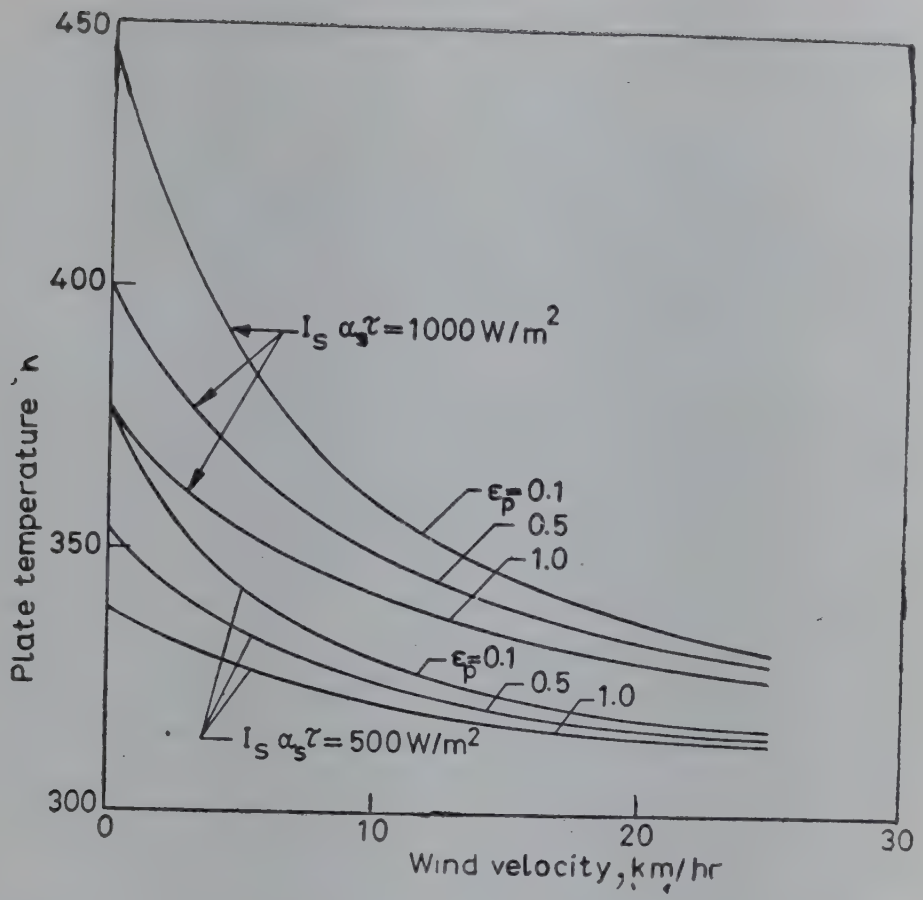


Fig. 3.1. Temperature of plate exposed to sun and wind

energy as possible, and convert it into useful energy, (which is heat in this case) at the highest possible temperature. The left hand side of the equation is the solar input term. It is evident that for maximum utilisation a_s should be as close to 1 as possible (most black paints, carbon black etc. have an a_s ranging from 0.85 to 0.98) and the absorber should be held normal to the direction of the sun, so that $\cos\theta_i = 1$, in $I_s = I_b \cos\theta_i + I_d$. On the right hand side of the equation, the first term is the convective loss due to flow of air over the collector, while the raditation loss is given by the second term. The temperature achieved by the plate is seen to depend very crucially on both, the convective and radiative loss. Convective loss is reduced by incorporating

a transparent cover which lets in solar radiation, while shielding the absorber from wind currents. A glass sheet when used as a cover also cuts down radiation losses,since it is opaque in the infra red region, where the collector emits its radiation. Use of a low emissivity coating ($\epsilon_c \simeq 0.1$) on the absorber also reduces the radiation loss. These effects are depicted graphically in the figure 3.1.

Guideliness for the design of a collector could then be summarized as follows : Firstly, all the radiation incident on the collector is to be absorbed, hence, the absorber plate should have a high absorptivity, while a high degree of transmitivity is required for the cover. Further, the orientation of the flat–plate should be such that all year round, the solar incident angle is optimal (it should be noted that flat-plate collectors do not track the sun). Therefore in the northern hemisphere the collector plate should be placed with its width along the east-west direction and facing south with a small 'tilt' to the horizon. Depending upon the application envisaged, i. e., whether the collector has to deliver most energy in the summer only, or the winter, or should have maximum annual energy delivery, the angle of tilt will be different. Losses by conduction, convection and radiation are to be reduced. By providing insulation (such as glass wool, mineral wool, rigid polyurethane foam, etc.) below and on the sides, conduction losses are reduced; whereas, convection losses are cut down by using an insulative transparent cover on top. Glass is the common cover material. Plastics such as acrylic plexiglass, polyethyelene, PVC, while having suitable properties cannot be used, since they are rapidly degraded after exposure to sun (the small amount of ultraviolet radiation contained in solar radiation does the damage). However UV stabilised plastics or PTFE, Tedlar etc., can be used. Thermal resistance of the cover can be increased by increasing the thickness of glass, but a better method is to use two or more thin layers of glass separated

by layers of air. Such a sandwich will have a thermal resistance far higher than a single thick layer. Radiation loss is reduced by the presence of the glass cover, although the emissivity of glass in the long wave region is close to 1, i.e. $\epsilon_g \simeq 1$ (while that in the short wave length region is nearly zero i.e. $\alpha \simeq 1.0$). This is because the glass cover is at a temperature lower than that of the absorber plate, and hence counts for less radiation, thus, acting as a radiation shield. Additional reduction can be achieved by using a spectrally selective coating for the absorber plate which is black only in the short wave lengths (i.e., $\alpha_s \simeq 1$) and has a low emissivity for long wave lengths ($\epsilon = 0.1$). The graphs shown in the figure 3.1 highlight these aspects.

While these considerations deal only with trapping solar energy effectively, other factors play an important role in determining how this trapped energy is transferred to the fluid which is to be heated.

In tube and plate type collectors (see Fig. 3.2b, described in section 3.2), heat is transferred through the plate to the tube walls by conduction, and from there to the fluid by convection. For efficient and rapid transfer of heat, the resistance to heat flow should be as small as possible. Hence, the need for high fluid flow rates and materials having a high conductivity (metals like copper or aluminium). This alone would not ensure the best operation, since the other term $q = mc \frac{dT_p}{dt}$, is also to be reduced. Heat capacity c, as well as the mass m, of the collector, affect this stored heat term, and thus implies that materials with low heat capacity and low thermal mass are to be preferred. A little more detailed analysis of the collector is presented, so that more details like the efficiency and the relative magnitudes of the terms involved can be examined.

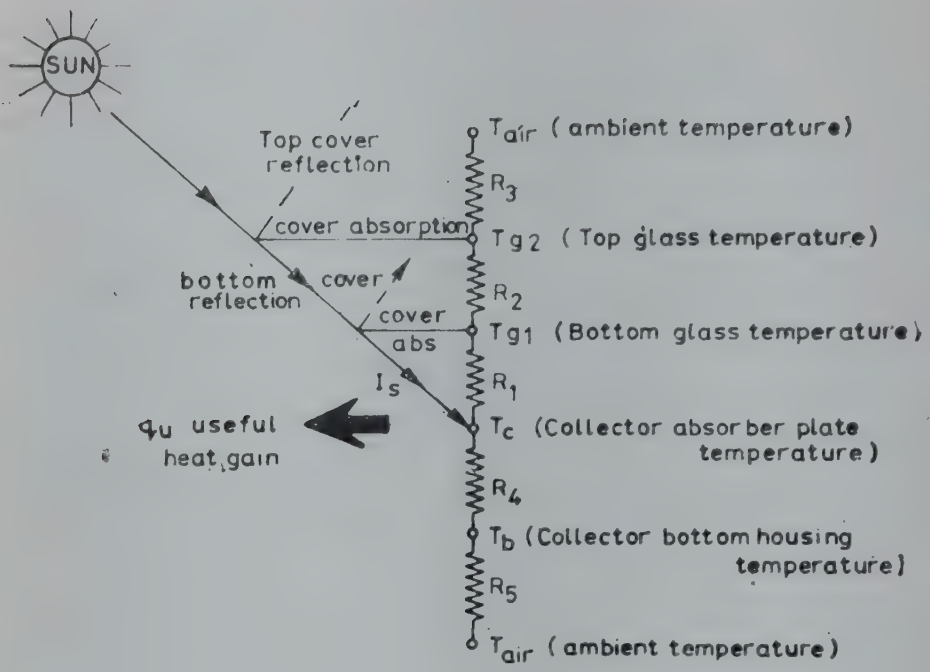


Fig. 3.2 (b) Thermal circuit for the collector

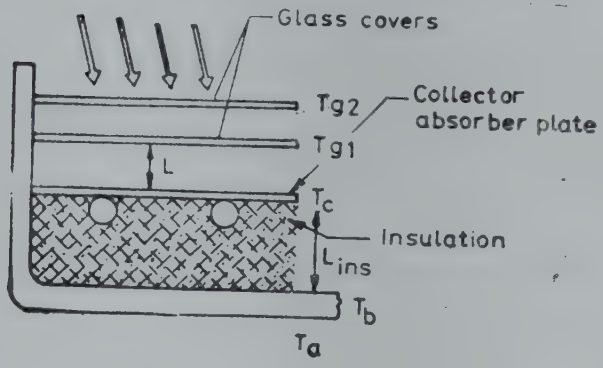


Fig. 3.2(a) Cross section through a typical tube & plate type collector

3. 1. PERFORMANCE OF COLLECTOR

Since the most common type of collector is the tube and plate type, a detailed analysis is presented for this type of collector. With slight modifications, it is possible to extend this analysis to any other kind of design. Figure 3.2b shows the cross section through such a collector. An instantaneous efficiency and an average efficiency can be defined as :

Instantaneous efficiency : $\eta_c = Q_u/(A_c I_s)$ .....(2)

Average efficiency : $\bar{\eta}_c = \int Q_u dt / \int A_c I_s dt$ .....(3)

where t is the time period over which the performance is averaged. Instead of writing the heat loss terms separately as in equation (1), the total heat lost from the collector-absorber plate to the surroundings can be written in a simple form :

$q_{loss} = U_c A_c (T_p - T_a)$ .....(4)

where U_c is the sum of top losses and back loss.

$U_c = U_T + U_B$ .....(5)

A thermal circuit diagram for analysing all the heat losses is showin in figure 3.2 (a)

If double glazing is used, the top loss coefficient U_T is given by

$$U_T = \frac{1}{h_{p-g1} + h_{rp-g1}} + \frac{1}{h_{g1-g2} + h_{rg1-g2}} + \frac{1}{h_w + h_{rg2-sky}} \quad ....(6)$$

Where the coefficients for convective heat transfer are denoted by h and h_r, and the subscripts denote the transfer between two surfaces. For example h_{p-g1} is the convective heat transfer coefficient between the absorber plate and the lower glass cover. It is a measure of the convection between two parallel surfaces and is given by [4]

$$h_{p-g1} = \frac{\overline{Nu}}{L} K_{air} \quad .....(7)$$

Where Nu denotes the Nusset number [4]. For an optimised design of solar collector, the space L between the collector absorber plates and the bottom glass is to be determined for minimum convective losses. The heat transfer between the hotter bottom plate (collector at T_p) and the cooler top plate (glass cover at T_g) occurs purely by cond-

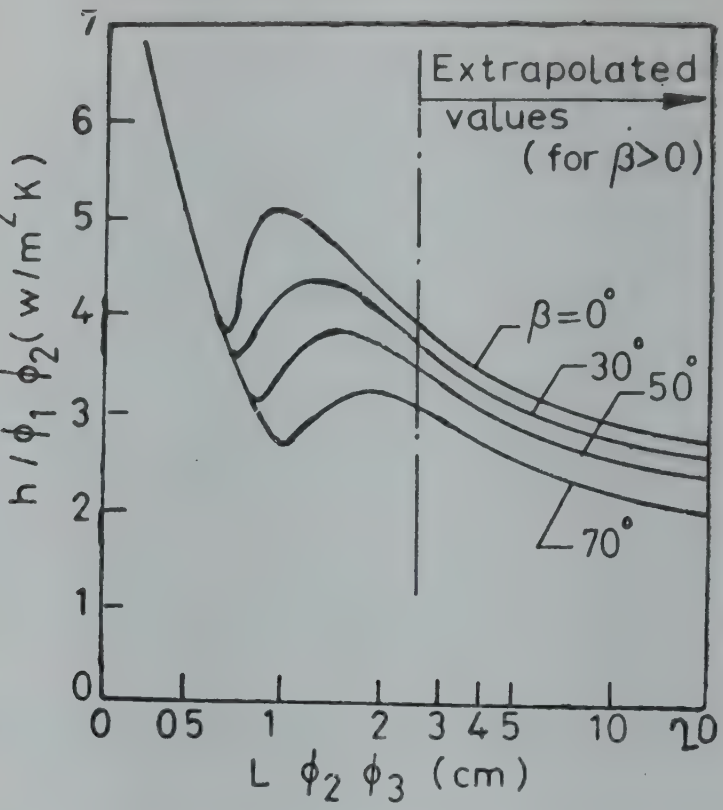


Fig. 3.3. Convective heat loss coefficient for the convective transfer from absorber plate to cover shown as a function of L, the gap between absorber plate and cover.

uction, when the spacing L and tempeature difference (T_p-T_{g1}) are such that the Rayleigh number is less than 1708, for the collector placed in a horizontal position (if tilted this becomes 1708cosβ). The Rayleigh number (Ra) is the product of the Grashof number (Gr) and the Prandtl number (Pr), and compares the buoyancy force caused by the heating of the fluid to the viscous forces. These numbers are given by :

$$Gr = \frac{g\beta \triangle T L^3}{\nu^2} \quad , Pr = \frac{\mu C_p}{k} = \frac{\nu}{a} \qquad \text{.....[8]}$$

$$Ra = Gr.\ Pr = \frac{g\beta \triangle T L^3}{a\nu} \qquad \text{.....[9]}$$

If the Rayleigh number exceds 1708, convective flow starts. The Nusset number has been found for a number of enclosures, and the coefficient h_{p-g1} calculated from this is shown in the figure 3.3. From the graphs in figure 3.3 it is found that the smallest convective loss corresponds [4] to

$$L_{min} = \frac{0.71}{(\cos\beta)^{1/3}\phi_2\phi_3} \text{ cms.} \qquad \text{.....[10]}$$

$$\phi_1 = \frac{464}{[T_m + 200]^{1/3}\, T_m^{1/2}} \qquad [11a]$$

$$\phi_2 = [\,[T_p - T_{g1}]/50\,]^{1/3} \qquad [11b]$$

$$\phi_3 = [\,1428[T_m + 200\,]^{2/3}/T^2_m \qquad [11c]$$

where $T_m = [T_p + T_{g1}]/2$ [11d]

Where all the temperatures are in °K.

Now, $h_{r,p-g1}$ is the radiative heat transfer coefficient between the plate and the bottom glass g^1, and is calculated as follows :

$$h_{r,\,p-g1} = \frac{[T_p + T_g{}^1]\quad [T_p{}^2 + T_{g1}\,]}{\left(\dfrac{1}{\varepsilon_p} + \dfrac{1}{\varepsilon_{g1}} - 1\right)} \qquad \text{.....[12a]}$$

For most practical purposes, this quantity h_r can be treated as constant, because over the limited range in which T_p and T_{g1} vary, the term $[T_p{}^4 - T^4{}_{g1}] \,/\, [\dfrac{1}{\varepsilon_p} + \dfrac{1}{\varepsilon_g{}^1} - 1]$ is fairly accurately given by $h_{rp-gI}\ [T_p - T_{gI}]$, with the value of h_r calculated for some average value of T_p and T_{gI}.

$$h_{r,\,g2-\,ky} = \sigma\varepsilon_{g2}\,[T_{\,2} + T_{sky}]\,[T_g{}^2{}_2 + T^2{}_{sky}]\left(\frac{T_{g2} - T_{sky}}{T_{g2} - T_a}\right) \text{....[12b]}$$

T_{ky} is the radiative temperature of the sky and it is given by some empirical relations like

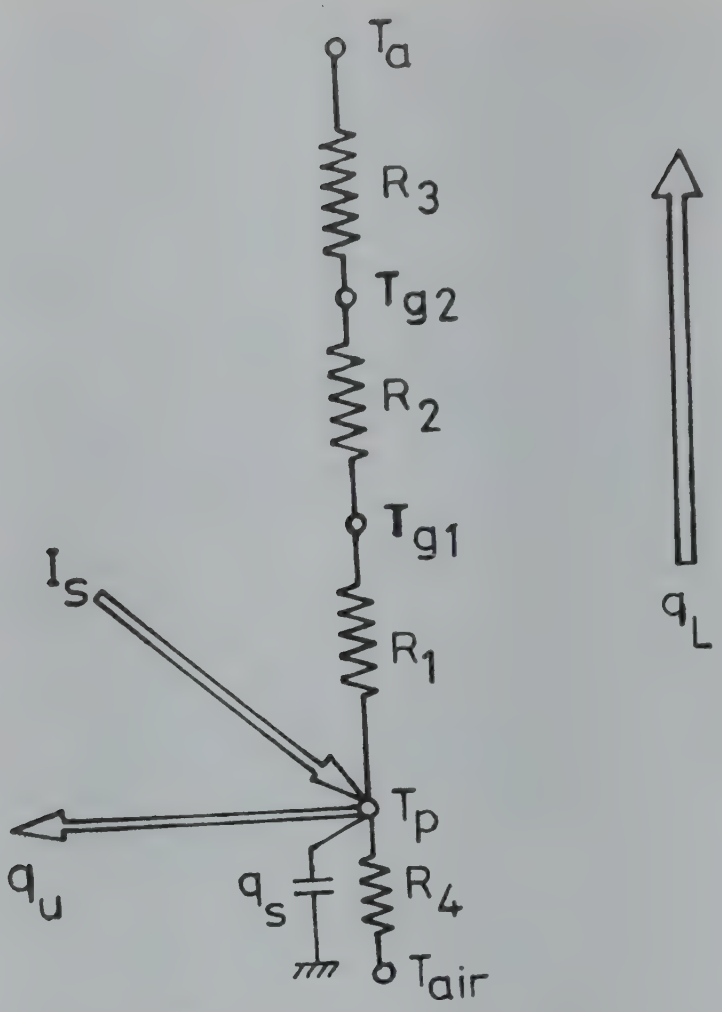


Fig. 3.4. Simplified thermal circuit for the flat-plate collector

$T_{sky} = [T_a - 11]°C$ or

$T_{sky} = [0.55 + 0.33\sqrt{P_{aw}}]\cdot^{25}T_a°K$ or

$T_{sky} = 0.99552\, T^{1\cdot5}{}_a\ °K$ .....[13]

It is to be noted that in these heat loss terms, the temperatures T_p, T_{g1} and T_{g2} are not known until the energy balance relation is solved. So as a first step, the coefficients are obtained by making a guess of the glass cover and collector temperatures.

The energy transfer q_1 between the plate at T_p and the bottom glass cover at T_{g1}, is the same as beetwen two

adjacent glass plates, and is equal to the energy lost to the sourroundings from the top cover glass (see fig. 3. 4)

$$q_{1,T} = U_T (T_p - T_a)$$

$$= \frac{1}{R_1} [T_p - T_{g1}] \quad \text{.....[14]}$$

$$= \frac{1}{R_2} [T_p - T_{g2}] \quad \text{.....[15]}$$

$$T_{g1} = T_p - U_T R_1 [T_p - T_a]$$

$$T_{g2} = T_{g1} - U_T R_2 [T_p - T_a] \quad \text{.....]16]}$$

In well insulated solar panels, the external convective resistance of the case is much smaller than the insulation resistance, i.e. $R_5 \ll R_4$ and the back loss conductance is given by

$$U_B = \frac{1}{R_4 + R_5} \approx \frac{1}{R_4} = \frac{K}{L_{ins}} \quad \text{.....[17]}$$

$$U_c = U_T + U_B = [1/(R_1 + R_2 + R_3)] + [1/R_4] \quad \text{.....[18]}$$

Now using the energy balance relations equations (1), (14), (15), (16), the temperatures T_p, T_{g1} and T_{g2} are found. The resistances R_1, R_2, R_3 and R_5 [see fig. 3. 4] are given by: $R_1 = 1/[h_{c-g1} + h_{r,\,c-g1}]$; $R_2 = 1/(h_{g1-2} + h_{r,\,g1-g2}]$

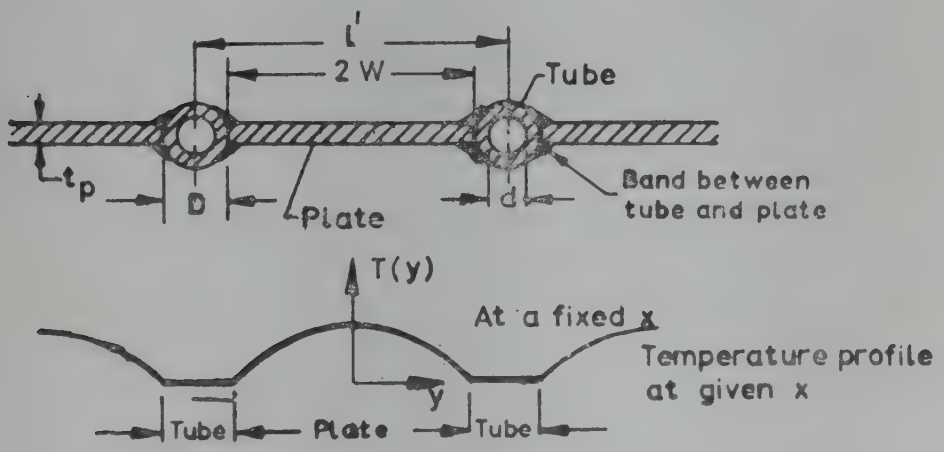


Fig. 3.5. Temperature distribution across a section of the collector.

$$R_3 = 1/[h_w - h_{r,c-sky}] \; ; \; R_4 = \frac{L_{ins}}{R_{ins}} \; ; \; R_5 = \frac{1}{h_{case-air}} \quad \text{.....[19]}$$

If T_{g1} and T_{g2} are close to the initial guess, no further calculations are necessary. Otherwise, the newly calculated T_{g1} and T_{g2} are used and the process is repeated.

3.1.1. Useful Heat Removal from the Collector

The heat collected by the absorber plate is to be transferred effectively to the fluid which is either water or air.

The flat-plate lying between two neighbouring tubes acts effectively as a fin (acting in reverse), transferring heat by conduction to the tube along the base of the fin (see fig. 3.5), while at the same time the fin suffers heat loss at the rate of U_c.

The fin efficiency F_N is defined as the ratio of the rate of heat transfer with a real fin to the maximum rate obtainable [4].

$$F_N = \frac{\tanh mw}{mw} \quad \text{.....[20]}$$

where $m = \left(\frac{U_c}{K_p t_p}\right)^{1/2}$

When the fin efficiency approaches unity, the maximum amount of the radiant energy impinging on the fin, becomes available for heating the fluid.

The material used for the plates and tubes (e.g. galvanized iron, steel, copper or plastic) and the bonding technique used to connect the two, affects the performance, because thermal diffusion (conduction) has to occur from the plate to the tubes. F_p the collector efficiency factor is given [4] by :

$$F_p = [U_c l \{U_c [d + 2wF_N]^{-1} + t_b[k_b l_b]^{-1} + t_t[k_t d]^{-1} + [h_f d_i]^{-1}\}]^{-1} \quad \text{.....[2]}$$

F_p is the ratio of the thermal resistance between the collector surface and the ambient air, to the thermal resistance between the fluid and the environment.

Depending on the method of circulation, i.e. natural circulation (thermosiphon) or forced circulation (induced by a pump], the velocity of flow of fluid, and hence, the rate of heat transfer h_f can be different. The effectiveness of heat transfer can be calculated by the usual methods in heat transfer analysis. The result of such an analysis yields the following relation [4] :

$$q_u = F_r \{a_s T_s I_s — U_c [T_{f,i} — T_a]\} \quad \text{.....[22]}$$

F_R, the collector heat removal factor is defined as the ratio of the actual rate of heat transfer to the working fluid to the rate of heat transfer at the minimum temperature difference between the absorber and the environment.

$$F = F_p F_f$$

$$F_f = \frac{Gc_p}{U_c F_p}\left\{1 — \exp\left(\frac{U_c F_p}{Gc_p}\right)\right\} \quad \text{.....[23]}$$

3.1.9. Transmittance through the covers

Whenever light travels through an interface separating two media, whose refractive indices are different, a part of the light is reflected and another part is transmitted and/or absorbed. Reflection of unpolarized light on passing from a medium refractive index n_1, to a medium with refractive index n_2 is given by [4] :

$$\rho = \frac{\sin^2(\theta_2 - \theta_1)}{2\sin^2(\theta_2 + \theta_1)} + \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} \quad \text{.....[24]}$$

where θ_1 and θ_2 are angles of incidence and refraction. In the above expression the two terms in the square brackets represent the relation for each of the to components of polarization. Reflectance ρ gives the reflection of unpolarized light as the average of the two components,

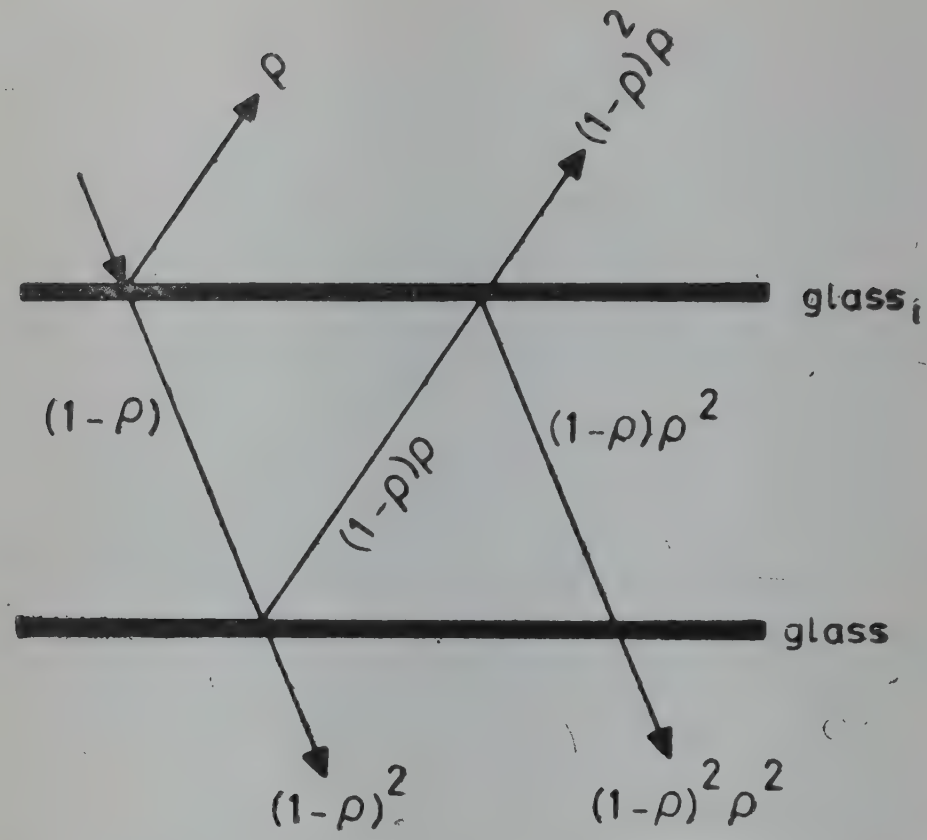


Fig. 3.6. Diagram showing the path of a ray of light through a set of two transparent cover suffering reflection at the interfaces.

$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{n_{glass}}{n_{air}} = n_{glass} \qquad (n_{air} \approx 1) \qquad \text{.....(25)}$$

For normal incidence both θ_1 and θ_2 are zero, and

$$\rho\ (\theta_1 = 0) = \left(\frac{n-1}{n+1}\right)^2 \qquad \text{.....(26)}$$

The transmittance for a single cover, neglecting absorption is then

$$T_{r,1} = \frac{1-\rho}{1+\rho} \qquad \text{.....[27]}$$

For a system of n covers

$$T_{r,n} = \frac{1-\rho}{1+[2n-1]\rho} \qquad \text{.....[28]}$$

This relationship holds for each of the two components of polarization. The transmittance for initially unpolarized light is found by taking the average transmittance of the two components.

If absorption of radiation in the transparent medium is considered, then according to Beer's law, which is based on the assumption that the absorbed radiation is proportional to the local intensity in the medium and the distance x, the radiation travels in the medium,

$$dI = -I \kappa \, dx \qquad \text{.....[29]}$$

Integrating the above equation between limits 0 and L_g we get

$$T_a = \frac{I_{cut}}{I_{in}} = \exp(-\kappa L_g) \qquad \text{.....[30]}$$

T_a is the transmittance, considering only absorption, and L_g is the actual path of radiation, through the medium. Since the radiation traversing a transparent cover suffers both reflection and absorption losses, the actual transmittance T, is the product of the two transmittances, T_r and T_a, i. e.

$$T = T_r T_a \qquad \text{.....[31]}$$

3.2. CONSTRUCTION OF FLAT-PLATE COLLECTORS

3.2.1. Storage type of heaters

The simplest of all flate-plate collectors would be an insulated box in which water is stored, and has a sheet of glass or plastic, as a cover (see fig. 3.7 a). Such a device would be very inexpensive and would be easy to construct and use. But the disadvantage of such a device is that the water vapour produced inside, starts condensing on the inside of the cover plate, causing an increased heat loss from the cover and thus lowering the efficiency. This problem can however be mitigated by incorporating two covers, one of which is in contact with the water surface and another above it (see fig. 3.7 b). A third variation (see fig. 3.7 c) is to use

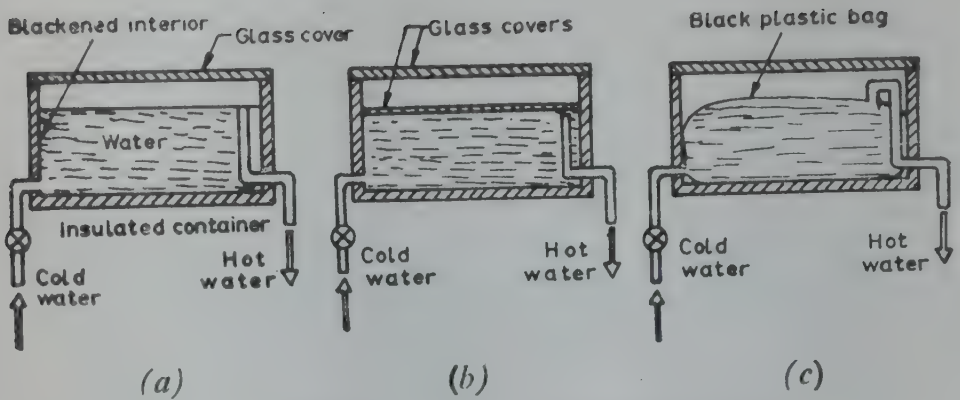


Fig. 3.7. Sample Storage type water heaters.

a black plastic bag containing the water to be heated. Such heaters can be made out of masonry material with a layer of insulation.

The principal drawback with these devices is the low efficiency, and lack of control over the temperature attained by the water,

3.2. 2. **Tube and plate type of collectors**

There are several basic configurations employed in tube and plate collectors. The simplest of which, is to have two heaters at either end of the collector, connected by a bank of pipes. A flat–plate is then laid over these pipes, and connected mechanically, by tying down with wires as shown in fig. 3.8 (a). While such construction is simple, it is also very inefficient in view of the poor thermal contact between the plate and pipes. The next step is to weld, braze or solder the plate to the pipes. Another type of collector is made by using two formed or corrugated sheets, such that ducts for circulating the fluid are formed (see fig. 3.8 b), when the two sheets are put together. Here, the two sheets, and the ends, can either be pressed together and closed or soldered, welded or brazed.

An elegant method of forming flow passages in the flat plates, is by Roll bonding, which is similar to what is done

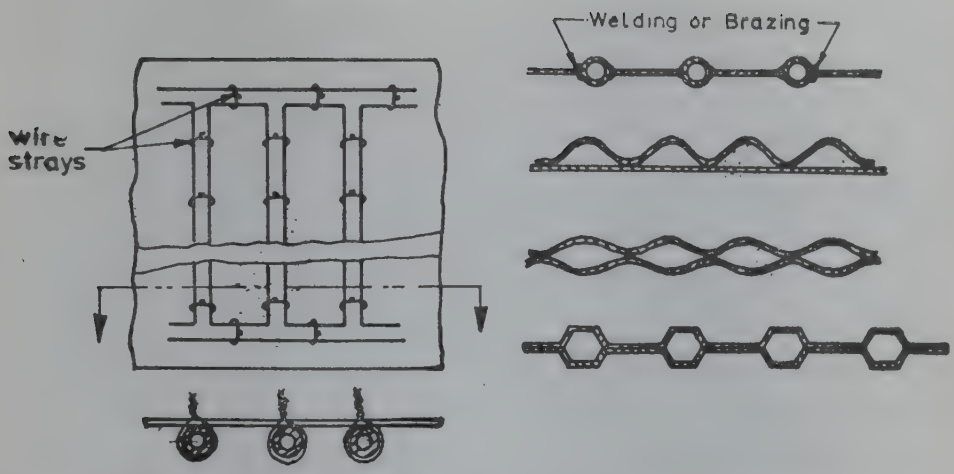


Fig. 3.8(a) Tube and plate type water heaters. *(b) Cross Sections through different type o collectors.*

for flow ducts, for the refrigerant in the freezer compartment of refrigerators.

The collector panel thus formed, is then kept inside a case and some insulation – glass wool or rigid plastic foam is placed between the case and panel. One or more glass plates are used to cover the top of the case.

Different kinds of materials have been proposed and tried, for making the collector panel. Metals like copper, aluminium, mild steel, galvanized iron, moulded plastics, with or without fibre reinforcements, cement or other masonry materiel etc., have been used. Each of these have their advantages and drawbacks.

As already seen, the heat energy, collected has to be transported from the plate to the pipe, and from the pipe to the fluid. To ensure a good performance, the energy stored in the material of the collector, itself, should be small. If we examine the heat transfer process for fin effectiveness first, it is seen that the fin efficiency is given by equation (20).

Thus for different materials of equal fin effectiveness the spacing between tubes is to be

$$w \propto \sqrt{K_p\, t_p} \quad \text{or} \quad w/\sqrt{K_p\, t_p} \quad \text{constant,} \quad \ldots\ldots\ldots[32]$$

for the same U_c. In other words the plate thickness t_p, is inversely proportional to the conductivity, if the same spacing is maintained. For example, if the spacing is such that $w = 50$ mm, and a fin efficiency of at least 95% is desired, then a copper plate of thickness 0.29 mm is required; while for aluminium it is 0.54 mm and for steel it is 2 mm when $U_c = 7 W/m^2°C$.

The next step in the heat transfer process, is the flow of heat across the bond, between the plate and tube, then across the tube wall and then into the fluid. The total resistance is then,

$$R = \frac{t_b}{K_a\, l_b} + \frac{t_t}{K_t \pi d_i} + \frac{1}{h_f \pi d_i} \qquad \ldots\ldots\ldots\ldots[33]$$

and the overall plate efficiency factor F_p is given by equation (21).

It is seen that for high efficiencies the bond conductivity is to be high(k_b has to exceed 35 W/m°C). Crude constructional techniques, depending on clamps or wire ties, for contact between the plate and tubes, invariably give lower thermal conductivity, and hence, do not perform well enough. The collector plate efficiency factor increases with : (a) increasing plate and tube thickness and their thermal conductivity, (b) decreasing spacing between tubes, (c) increasing fluid flow velocity (i. e. increasing film heat transfer coefficient), (d) descreasing overall heat loss coefficient U_c. For example, to get a value of $F_p = 0.9$, (when $U_c = 7 W/m^2°C$, with 12 mm I. D. tubes having a laminar flow of water in tubes, giving $h_f = 340 W/m^2°C$ and a tube spacing of 10 cms) a copper collector with 0.25 mm thickness is sufficient, while for aluminium 0.53 mm and for steel 2.0 mm thickness for t_t and t_p is

required. If now h_f is increased to 1700 W/m^2°C (flow being turbulent) then F_p increases to about 0.95.

Due to the difference in temperature, that exists between the fluid at its entry into the collector, $T_{f,i}$ and at the exit, $T_{f,o}$, a further reduction in the energy transferred to the fluid (when compared to what is possible) occurs. This is the flow factor F_f, equation (23). When all these efficiencies are included, the useful heat removed is given by equation (22.)

It is seen from equation (23) that as the rate of flow of fluid increases and U_c decreases (i. e. Gc_p/U_cF_p increases), F_f increases. However, it is not possible for F_f to exceed F_p in any case. The above considerations indicate that for the tube and plate type of collectors a rational design procedure would consist of optimising several parameters listed here : k, t_p, t_t, w, d_i, U_c, h_f, m

Unfortunately what may be optimum from a performance point of view, would most certainly be highly expensive, and hence not feasible, since the cost of the collector has to be kept in mind. It turns out that (10) there is an upper limit for the cost/m^2 of the collector, with a given performance coefficient, for the solar flat – plate collector to be cost effective. This number then sets an upper limit to the weight of the collector since the cost can be roughly related to the weight.

3.2.3. Water circulation

So for we have only examined the collector panel. What ever the fulid that is to be heated, has to be circulated and then stored if necessary. Water heaters are commonly constructed in two forms : those having natural convection (thermosiphon) or those with forced circulation (with a pump). When thermosiphon circulation is used (see fig. 3.9(a)), a flow is created by the difference in density and hence a pressure

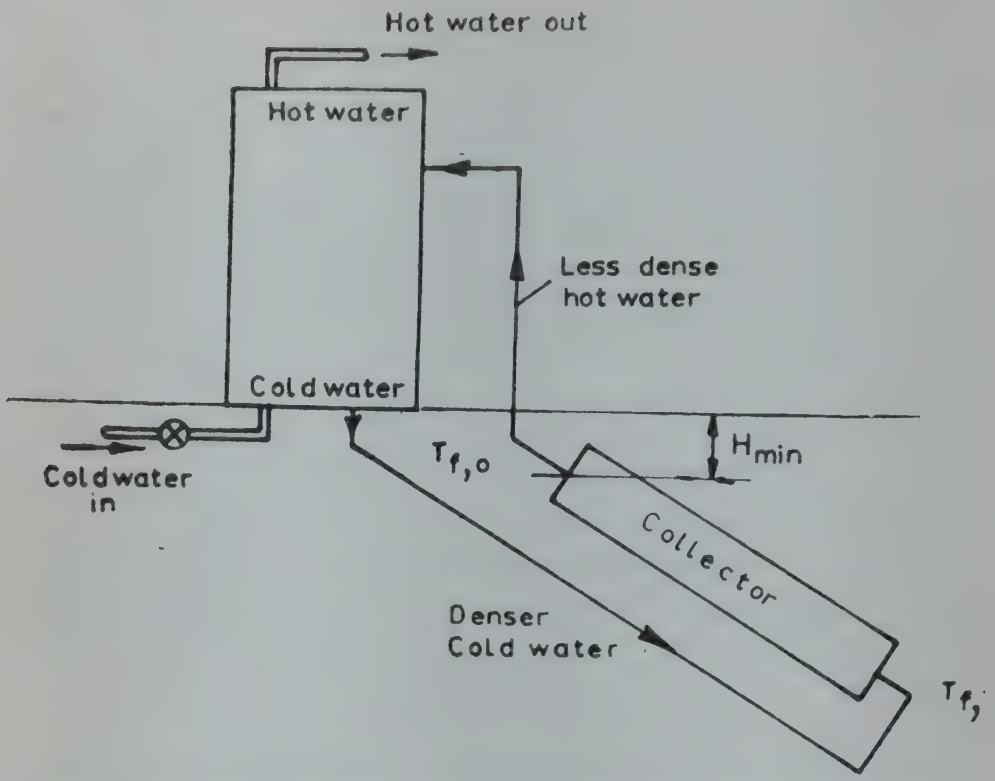
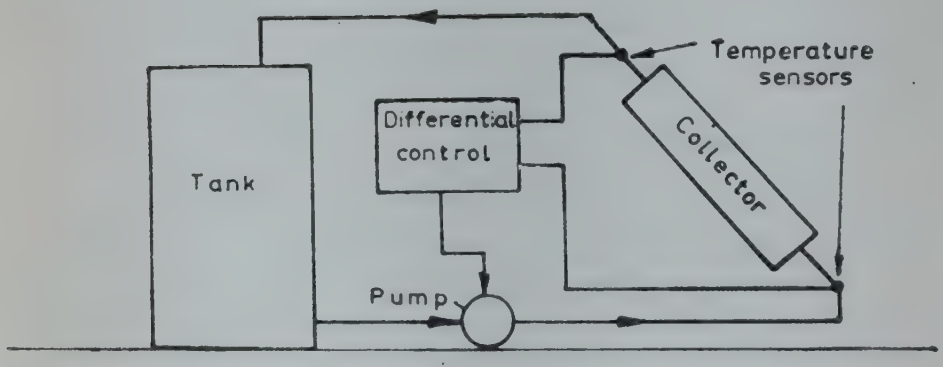


Fig. 3.9(a) Schematic representation of thermosiphon circulation.



Forced circulation

Fig. 3.9 (b) Schematic representation of Forced circulation

head) is caused bythe warmer water at the tap and the cooler water at the bottom. This pressure head gives rise to a flow that is self regulating. No flow can occur, unless the difference in temperature is large enough to give rise to a pressure head that is sufficient for overcoming the frictional losses in the plumbing. Usually a 10°C rise in temperature, (i.e. $T_{f,o}$— $T_{f,i} = 10°C$) is necessary for flow to occur in systems that have no serious flow restrictions. This implies that, water in the tank will be circulated a number of times before reaching a desired temperature of 60 or 70°C. The flow velocities are fairly low, and only laminar flow can occur, with this kind of a device.

With forced circulation systems, (see fig. 3.9b) higher flow velocities can be attained with a consequent lower temperature rise, per pass. But in such systems, a control system is required to stop the flow when the temperature rise after a pass, falls below say 2°C. So a differential controller for operating the pump is essential. In spite of the fact that the overall performance of a forced flow system should be better than a thermosiphon system (whose flow velocities are much lower and hence have a lower h_f), in parctice the performance of the two kinds of systems is indeed more or less the same. The simple system that results from a thermosiphon is an added attraction. But it should be noted that certain precautions are to be taken while making a thermosiphon circulating system. The water storage tank should be positioned at a certain minimum height H_{min} above the collector panel. If this is not done, the collector surface which acts as a radiative cooler causes a reverse circulation of the hot water in the tank, thus effectively cooling the water during the night. Another aspect that needs to be emphasized is that since the thermosiphon needs a pressure head derived from density differences, a separate water tank is required for each panel. In large systems wherein many collectors are to be connected,

this would not be parctical. However a distributed tank (for example a large bore pipe header) can be used for this purpose (11).

3.2.4. Other types of water heaters :

Many variations of the basic types of heaters considered in sections 3.2.1 and 3.2.2 have been developed and are in use. In one such device a long black plastic hose which has been coiled and housed inside an insulated box with a transparent cover, replaces the collector. A variation of this scheme is to use a transparent plastic hose and circulate water coloured black, by the addition of a dye. This is an improvement over the black hose system, since the water, here, is heated. Whereas in the case of the black hose system, the heat has to be conducted through the wall of the hose, which is a poor conductor. However, in the second system, a second loop is required, wherein the black water is circulated in a closed loop ; while the water that is to be heated gets its heat from the hot black water. Such collectors are simple and inexpensive, although they are less efficient. Another type has a storage tank at the top end of the collector. Another innovative device is the trickle flow collector. Here the collector is merely a black corrugated sheet. A header at the top edge of the collector allows the fluid to be heated, as drops through small holes drilled in the header. These fluid drops get heated as they trickle down along the corrugated channels, until they reach the bottom of the plate, where they are collected. These collectors are also simple in construction but have a low efficiency.

3.3. Materials for Collectors ;

We have already seen that the three major components of the collector are glazing, absorber plate and

the casing. Besides the collector there is the storage tank, plumbing and control system to be considered.

3.3.1. Glazing

The main requirement for glazing, is that it should have a high transmittance in the short wave length region (i.e. $\lambda < 3\mu m$) and a very low transmittance in the long wave length region ($\lambda > 3\mu m$). Common sheet glass (soda glass) suits the purpose well. The transmittance of glass depends mostly on the amount of Fe_2O_3 contained in the glass. The lower the composition of Fe_2O_3 the better the transmittance. Common window glass contains upto 0.15% of Fe_2O_3. The transmittance of such a glass sheet of 5 mm thickness would be about 90%, in the 0.35 to $3\mu m$ region. The 10% loss is due to absorption in the glass, and also due to reflection of part of the radiation at the upper surface of glass, called Fresnel reflection [4]. While the absorption loss can be reduced, Fresnel reflection cannot be reduced. For normal incidence this Fresnel reflection coefficient is given by equation (26), where $\rho = 0.04$ if $n_{glass} = 1.5$.

This loss can be reduced by 4%, only if an antireflective coating is applied to the surface. So, if more than one sheet of glass is to be used, it should be remembered that both reflective and absorption losses increase with number, thus the transmittance is considerably reduced.

Plastics have very desirable properties like toughness, flexibility, low cost, availability in the form of thin sheets or films, etc. But then, disadvantages like low resistance to scratching and abrasion, inability to withstand high temperatures, poor weatherability have prevented their large scale use. Recently several fluorocarbons like Teflon, Tedlar etc., with good wea-

therability are becoming commercially available, as thin films for glazing purposes.

3.3.3 **Absorber plate**

We have already seen that for efficiently transferring heat from the absorbing surface to the fluid, materials with high thermal conductivity are required. Apart from the noble metals which have very high thermal couductivities, copper (k = 393.56 W/m°C,) Aluminium (k = 217.71 W/m°C) have good conductivities, while steel (k = 66.99 W/m°C) has a fairly low conductivity. Plastics and masonry materials have a much lower conductivity [K = 0.2 to 3/W m°C] and are not preferred. But the main constraint on the choice of the material is the total cost of the collector. It is easily seen that if the cost of the collector doubles, e.g if copper is used instead of steel, then the total energy collected by the device should also double, (i.e. F_R for the copper collector must be so much larger than that of steel collectors) so as to justify the cost, all other cosiderations being the same (like life of collector, availability of space). However this is not the case. Hence, the choice of material has to be based on a rational optimisation of cost, performance and other factors.

Plastics have the advantage of having a lower density. The cost of the collector is directly related to its total weight, on the average about Rs. 25/— to Rs. 40/- per kg. When plastics are used, the weight and the cost would come down considerably. To some extent the poor performance of plastic, could be mitiga- by the lower cost.

3.3.3. **Black Coatings**

Black paints, lamp black, selective substances are all in use as absorber coatings on the metal collector plate. The black coating should absorb all

the solar radiation, i,e. α_s should be as close to 1.0 as possible, in the range of 0.3μm to at least 3μm wavelength and have a very low emmisivity, where the plate-emits. This implies that if the plate temperature is between 350-400° K, the emmissivity in the 5μm wavelengh should be close to zero. As the temperature of plate increases the re-emission peak wave length shifts towards shorter wavelengths as given by λ_{max} T$\simeq$0.293μm°K (Wiens law). Table 3.1 below gives the α and ϵ of commonly used black substances.

Table 3.1

Properties of coatings for the absorber plate

	Coating	Short Wave Absorptance	Long Wave Emittance
1.	Black Enamel paint	0.83	0.83
2.	Tar	0.86	0.86
3.	Lamp black	0 95	0.95
4.	Nickel black (oxides & sulfides of Ni & Zn) on polished Ni	0.91-0.94	0.11
5.	Nickel black on galvanized iron	0.89	0.16-0.18
6.	Nickel black–two layers on electorplated Ni on mild steel	0.94	0.07
7.	CuO on Ni (Electro-deposition of Cu and subsequent oxidation)	0.81	0.17
8.	Cu0 on Al (spraying Cu $[No_3]_2$ solution on Hot Al. plate and baking]	0.93	0.11

	Coating	Short wave Absorptance	Long wave Emittance
9.	Copper black on Cu [treatment with NaOH and $NaClO_2$]	0.89	0.17
10.	CuO on anodized Al [treated with hot Cu $(NO_3)_2 - KMnO_4$ solution and baked]	0.85	0.11

The technique of making cheap, long lasting, stable coatings which are spectrally selective are still being studied and there appears to be no single method which is superior to those currently in use.

3.3.4. Collector case

The housing which supports the glazing and the absorber plate can be made of metal, wood or other non-metallic materials like reinforced plastics (fibre glass), masonry, etc. Its main requirements are, structural rigidity and good weatherability with minimum of maintenance. If a metal box is used, corrosion from exposure to the weather, is to be prevented by proper passivation and painting. When such collector systems are installed on new buildings, they can be integrated into the structure of the building, the collector case can be totally avoided, thus bringing down the system cost.

3.3.5. Insulation

Insulating the absorber panel from the collector case is rather simple—involving as it does, provision of adequate thickness of insulating materials (see table 3.2.)

Table 3. 2.

Properties of common insulating materials

	Materials	Density kg/m³	Thermal conductivity W/m°C
1.	Mineral wool	12–14	0.0332 – 0.0404
2.	Hair felt	80	0.0389

Materials	Density kg/m³	Thermal conductivity W/m°C
3. Granulated cork	120	0.0476
4. Straw	10–13	0·0576
5. Saw dust	13–24	0.649
6. Vermiculite	128	0.0721
7. Polyurethane Rigid foam	24	0.0245
8. Polystyrene foam (thermocole)	16	0.0303

The bottom of the collector should have the provision of a 5 cm. thick insulation which will ensure a back loss coefficient of only 0.6 to 0.8 W/m²°C, when mineral wool or plastic foam is used. Polystyrene foam cannot be used if the expected temperature of the plate exceeds 80 or 90°C, while polyurethane foam is suitable upto temperatures of 150°C. Other criterion determining the choice of material are the cost of the insulation and the density of the material. If an insulating material of higher density is to be used, the resulting increase in weight, will require a stronger absorber case, to sustain the structure.

3.3.6. Use of Honeycomb Insulation

As rough measure, the various losses from the flat plate, operating at about 60 to 70°C in a 30°C ambient environment are shown in Table 3.3; the overall efficiency being of the order of 47 to 67%.

Table 3.3.

Loss in Flat-Plate collectors

Type of loss	Loss %
Edge	1–3
Back	5–10
Top-Radiation	5–10
Convection	22–30
Useful Energy	67–47

It is seen (refer Table 3.3.) that the heat lost by way of convection from the top is largest. To ensure a better performance, it is necessary to cut down this loss, by using more than one glass cover, or by using a transparent honeycomb structure above the collector plate to reduce convection losses [3,4]. Such honeycomb inserts, will divide the air layer between the cover and absorber plate into a number of cells. Care should be taken in selecting the size of these honeycomb cells, which if too large can actually increase the convective heat transfer.

3.3.7. Storage Tanks

Hot water can be stored in storage tanks, fabricated from steel, fiberglass, aluminium, rigid P.V.C. or concrete. These storage tanks must be leak proof, capable of withstanding long exposures to temprature variation, weathering and be corrosion resistant. To minimize the heat loss, the ratio of surface area to volume should be minimum (a sphere has the minimum surface to volume ratio) and spherical tanks are however difficult to fabricate and they consume a lot of space in building, and require special supports. The surface area of a cylindrical tank whose height is equal to its diameter, is only about 15% greater than that of a sphere, and is much easier to fabricate.

These storage tanks should be well insulated if hot water is to be stored in them. The optimal amount of insulation, is that which saves energy equal in value to the cost of the extra insulation that is required to provide that saving. The volume of the storage tank depends on the energy collection by the collectors connected to it.

3.4 Performance of Flat-Plate collectors

The instantaneous efficiency of the collector can be calculated from equation (2). But the true performance will be considerably different from the instantaneous efficiency, due to cloudiness, varying angle of incidence of solar radiation etc.

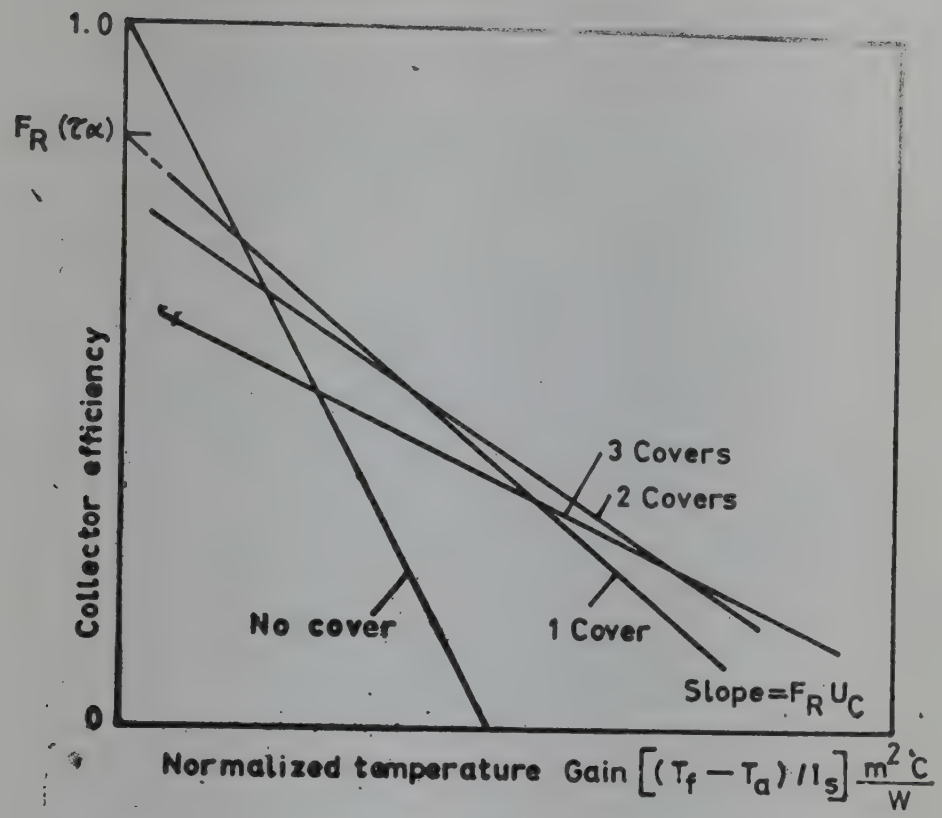


Fig. 3.10 Performance of a typical flat–plate collector

Fig. 3.10 illustrates the performance of a solar collector. Many conclusions can be drawn from the figure. As the temperature of operation is increased the efficiency drops rapidly, due to the increasing losses. The point where the curve interesects the y-axis corresponds to the $F_R(\tau\alpha)$ product for the collector, as seen from the equation (22).

It can also be seen that the slope of the line in fig. 3.10 gives the value of $F_R U_c$. The provision of multiple sheets of glazing, improves the efficiency, only when the temperature of operation is higher. At lower temperatures multiple glazing reduces the efficiency because of the lower $F_R(\tau\alpha)$ product of such devices.

To obtain a realistic estimate of the long term performance of the collector, another parameter called Utilization

Factor ϕ is used. A simple analysis leads to the defintion of ϕ. From equation (22) it is seen that until $I_s (\tau\alpha) > U_c (T_f - T_a)$, the term q_u is negative. In other words the useful heat delivered will be zero, until I_s exceeds a minimum quantity I_L where :

$$I_L = U_c (T_f - T_a)/(\tau\alpha) \quad \text{.....(34)}$$

Thus $q_u = F_R (\tau\alpha) (I_s - I_L)$, and since I_s increases from zero to its maximum value at solar noon and decreases again, the hourly value of q_u is to be found. A long term average of $q_{u,h}$ for any hour in the day can be found by averaging q_u over a number of days.

$$\bar{q}_{u,h} = F_R (\overline{\tau\alpha}) \frac{1}{N} \sum_N (I_s - I_L)^+ \quad \text{.....(34)}$$

The symbol $(\quad)^+$ implies that the summation includes only such terms for which $(I_s - I_L)$ is positive. The utilization factor ϕ is difined as :

$$\phi = \frac{1}{N} \frac{(I_s - I_L)^+}{I_s} \quad \text{.....(36)}$$

Where I_s is the long term average hourly solar radiation. Now the long term daily average useful energy collection is

$$Q_u = \sum_{h=1}^{n} q_{u,h} \quad \text{.....(37)}$$

It is found that this quantity ϕ, is a unique function of $I_L / \bar{I}_s$, for a given location and is nearly constant for all the hours, for one month. A further simplification is achieved by defining a monthly average of daily utilization $\bar{\phi}$ as :

$$\bar{\phi} = \sum_N \sum_{h=1}^{n} (I_s - I_L)^+ / (\bar{H}_s N) \quad \text{.....(38)}$$

Where $I_L = U_c (T_f - T_a)/(\overline{\tau\alpha})$, T_a and $(\overline{\tau\alpha})$ being monthly averages. It has been shown by Klein that :

$$\bar{\phi} = \exp [a + b (R_n/\bar{R})] [\bar{X}_c + C \bar{X}_c^2] \quad \text{.....(39)}$$

In this expression $X_c = I_L (r_n R_n \bar{H}_o \bar{K}_T)$ where $R = \bar{R}/R_n$ is the monthly ratio of the radaition on a tilted surface to the radiation on a horizontal surface. The values of a, b and c are [5] given in Table 3.4.

Table 3. 4.

Constants in equation (39)

K_T	a	b	c
0.3	0.521	-2.007	0.005
0.4	0.100	-1.389	0.178
0.5	-0.750	-0.785	0.414
0.6	-1.112	-0.389	0.638
0.7	-1.564	-0.115	1.158

After the utility has been calculated, the average daily energy collected by the solar panel, Q_u can be estimated directly, using the relation.

$$\bar{Q}_u = F_R (\bar{\tau}\bar{\alpha}) \bar{H}_T N \bar{\phi} \quad \text{.....(40)}$$

Here $\bar{H}_T$ = monthly average daily total solar radiation on the collector.

3.5. Design of Flat-Plate Collectors

When a solar water heating system is to be designed for a given application, a step by step procedure of design is to be followed. One such design procedure is outlined here. As a first step a rough and ready design is carried out which is followed up by a more detailed and precise design.

3.5.1. Sizing the area of collectors

The total energy requirement of the task is estimated, first. For example, if the heating system is intended for

domestic application-say for supplying bath water at 60°C, for five people at 12 noon–the energy needed is easily estimated as $mc_p (\triangle T)$ where = mmass of water to be heated, which is about 100 kg (at 20 litres/person) and $(\triangle T) = (60–25)°C$, taking the water inlet temperature as 25°C. The energy requirement is then 3500 kcal/day or 4.2 kWh/day. The average solar insolation in India is about 6 kWh day m^2, on a horizontal surface. The peak efficiency varies from 45 to 65%, (with $\triangle T = 35°C$. the efficiency will be closer to 60%). Hence the energy requirements work out to 3.6kWh/m2 day. But since the water is required by noon, only half the total daily solar radiation would be available. The area of collector required works out to be 2.35 to 2.8m^2. If an insulated storage tank is incorporated with the collector, water heated after 12 noon can be utilised and stored for the next day's use. In this case, taking storage efficiency into consideration, which is small, the total area of the collector comes down to 2m^2. But this is only a very crude estimate. A more meaningful estimate will result if the local meteorological data on the availability of solar radiation is examined. The season when the collector is to supply this energy, should also be know. For example, if this hot water were required for heating a home in winter, the collectors have to be optimised for maximum energy recovery In winter. Similarly if the heaters are used in conjunction with air conditioners, whose peak load is in summer, the collectors would have to be optimised for use in summer. On the other hand, if the heating system is intended for the round-the-year-use, the system should be so opitimised as to recover the maximum possible energy on an annual basis.

3.5.2. Collector tilt

Having determined the basis for optimisation, the collector tilt can be fixed. This tilt will ensure maximum collection during the desired season. Table 3.5 gives mean yearly collection on a tilted flat surface.

Table 3.5.

Effect of collector orientation on insolation

Latitude L	Azimuth A_z*	Inclination (tilt) β	Mean Annual Insolation Kwh/m², day
15	0	0	6.08
15	0	13.5	6.26
15	0	18	6.24
15	22.5	13.5	6.23
15	22.5	18	6.21
15	22.5	22.5	6.13
15	45	13.5	6.17
15	45	18.0	6.12
15	45	22.0	6.05
30	0	0	5.61
30	0	27.0	6.25
30	0	36.0	6.16
30	0	45.0	5.99
30	22.5	27.0	6.13
30	22.5	36.0	6·04
30	22.5	45.0	5.78
30	45.0	27.0	5.91
30	45.0	36.0	5.77
30	45.0	45.0	5.53

It is seen that the azimuthal orientation of upto 20 to 30° east or west of south, does not make much difference in the annual energy collected. On the other hand for optimum performance the tilt has to be as shown in Table 3.6 [3].

*Solar azimuth angle is defined as in Section 2.0, equation 6.

Table 3.6

Optimum Tilt β_{opt}

Year round optimum	0.9.L
Winter Optimum	L + 15°
Summer optimum	L — 15° or whichever is larger

3.5. Useful Energy Availability

Since the energy available on the fixed flat-plate changes over the different months, due to the change in the solar declination and cloudiness($\bar{K}_T$), it is necessary to estimate the amount of energy available during different months. As an aid to this, the curves shown in fig. 3.11 (a) given by Liu and Jordan [13], and Garg and Gupta (see fig. 3.11 (b) [3], can be used to estimate the useful energy that can be expected. The first set of curves (given by Liu and Jordan) are for collectors with two glass panes and a non-selective black painted absorber plate, tilted at L + 15°, for January and July. These curves give the long trem average daily useful collection, once K_T—the average cloudiness index is known. For other months the collection can be taken to be lying between the values for January and July. The second set of curves have been drawn for a flat-plate collector with a single glass cover, and the black painted absorber plate ($\alpha_s = \epsilon = 0.95$) tilted at L + 15° in January and L—15° in July. Thus it is observed that if the collector tilt is fixed at L+15°, the useful energy extracted is about 3.5 KWh/m² day when $\bar{K}_T = 0.7$, $F_R = 0.9$ for T = 35° in January-at Bangalore, while it is only 1.8 kwh/m² day for July when $\bar{K}_T = 0.5$, and even as low as 1 kWh/m² day for July.

It is evident then that sizing of the collector area should be based on the load requirement. In the example cited above, if bath water is to be heated to 60°C in the rainy

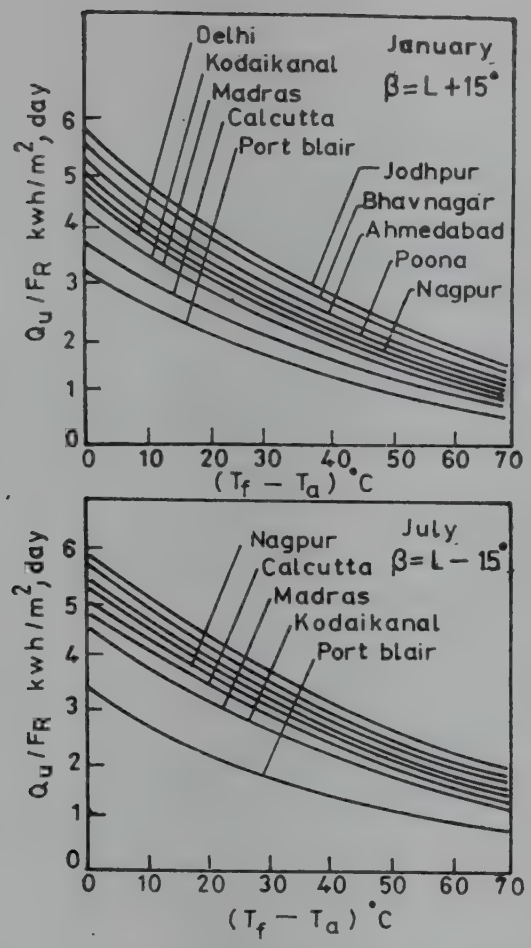


Fig. 3.11 (a) Solor Energy Availability

months (with small $\bar{K}_T$) then the area required becomes very large, and for some days the required temperature may not be achieved. In such circumstances, the sizing is best decided on the optimum year round operation, and provision is to be made for an auxiliary heater, to take care of the period when the available energy is below the requisite level.

3.5.4. Types of Collectors

As has been described earlier, there are many types of collectors available. The type of collector best suited for a given purpose, depends upon constraints like : capital cost,

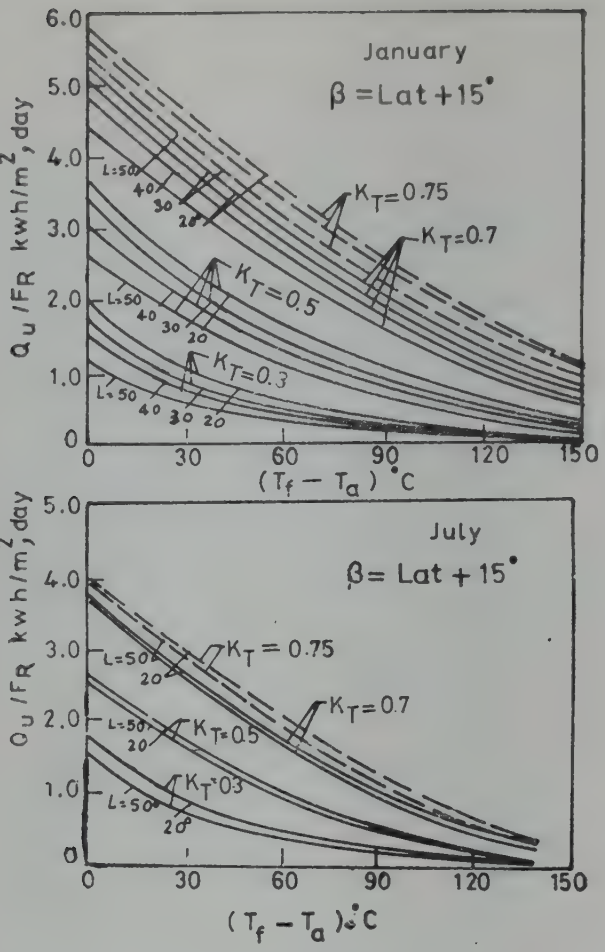


Fig. 3.11 (b) Solar Energy Availability

life, returns expected, nature of use, temperature of water required etc. The first three – cost, life and returns are all related ; for example, consider the simple plastic storage type collector described in section 3.2.3. Its cost is low, its efficiency is low, and hence the cost of energy collected will also be low, and it will have a life in the range of 1 to 2 years. But this may be quite adequate for domestic heating. On the other hand, a copper collector will have a high cost component, a longer life and moderate returns. Thus the annual returns would be :

$E_r \sum_N \bar{Q}_u$, where E_r = energy tariff.

Table 3.7

Type of collector	No. of Glass covers	Collector		Glass		Range of temperature rise (°C)	T_{out} °C	Remarks
		α	ϵ	α	ϵ			
1. Simple flat plate collector	1	0.95	0.95	0.9	0. 95	25-45	50-70	Most commonly available, cost Rs. 1000-1500/m², mode rate efficiency (40-60%.)
2. Multiple glazed flat–plate collector	2 to 3	0.95	0.95	0.81 to 0.73	0.9	45-60	70-85	Higher performance at elevated tempra-ture. Slighty more expensive Rs. 1300-1700/m²
3. Selective surface collectors	1	0.9	0.1	0.9	0.95	50–65	75–90	More expensive, better performance-Rs· 1500–1800/m²
4. Selective surface multiple glazing	2	0.9	0.1	0.88	0.9	60–85	85–110 °C	Even more expensive
5. Selective surface anti — reflection coating on glass	2	0.9	0.1	0.95	0.9	upto 95	120 °C	Very expensive, high performance

Table 3.8

Type of collector	Cost of collector Rs./m^2	Life of collector	Average Energy collected kWh/m^2 day	Annual Returns Rs.	Annual Returns %	Break even period: Collector only	Break even period: Entire system	Remarks
1. Storage type plastic heater	300	1 to 2 yrs.	2.0	200	67	$1\frac{1}{2}$ yrs.	$1\frac{1}{2}$ yrs.	Suitable for small domestic needs only
2. Galvanized iron collector + thermosiphon storage system	1000 +500	5 yrs.	3.0	300	20	$3\frac{1}{3}$ yrs.	5 yrs.	Domestic and industrial application. Breakeven possible only after 5 years of life.
3. Copper collector thermosiphon storage system	1750 +500	10 to 15 yrs.	3.3	330	15	$5\frac{1}{3}$ yrs.	6.8 yrs.	Best suited for industrial application, long life, high cost.

Returs calculated, assuming Rs. 0.33/kWh and 300 days use/year

If the capital cost is known, the returns as a percentage of the cost of collector and circulation system can be computed.

The choice of a type of collector, depends on the temperature of water required. The table 3.7 lists the necessary level of sophistication, as a function of the temperature expected.

Thus for domestic purposes, where the intial cost is low, either a small storage type of collector, a simple corrugated sheet galvanised iron collector (which is corrosion inhibited) or a copper collector can be used. The table 3.8 shows the relative returns.

3.5.5. Detailed design of flat-plate collectors

Having decided on the type of flat-plate cllector, the next task is to fix the material, sizes and dimension of each individual collector. The area of a collector is normally $2m^2$. If the area is reduced, the cost of packaging the collector increases, and a larger size will again impose higher costs, resulting from the increasing requirements of structural rigidity, etc.

Using the relations given in section 3.1 the thickness of the plate, spacing between tubes, diameter of tubes (which are normally taken to be 12.5 mm I.D.), headers (which are usually 25mm I.D.], method of construction. thickness of insulation, 5 to 10 cm thick), width of the gap between absorber plate and glass sheet, thickness of glass sheet, number of glass sheets, gap between glass sheets, (about 2-5 cms) coating on absorber plate and the design of the outer case, are carried out.

We shall illustrate the process with an example. Let the aim of the designer be, to obtain a value of 0.9 for F_R, and let thermosiphon circulation be used. If the total quantity of water heated in 8 hours through 50°C is 100 liters, then the average flow rate is $M = 100 \times 50 \times 1/[8 \times 60 \times 10) = 1.04$ kg/min

or about 1 litre/min, assuming a 70°C rise per pass. Using this flow rate the collector performance factor F_p is found from equation (23). Knowing the bond resistance and thermal conductivity of the material, the fin efficiency necessary to give the required value of F_p can be determined. This value of the fin efficiency will be reduced for some value of tube spacing, fin thickness and loss coefficient U_c, being fixed.

Instead of carrying out delailed calculations of U_c, as detailed in section 3.1, a first estimate of the total loss, q_{loss}, can be made, by using an empirical relation for top loss.

$$q_{top\ loss} = (T_p - T_a)\ \{(N^*/(0.165)\ [\ (T_p - T_a)\ /\ (N^* + f^*)\ ]^{0.31} + (\frac{1}{h_w})\ \}^{-1}\ Btu/hrft^2 \quad .....(41)$$

$$q_{bottom\ loss} = (T_p - T_a)\ k_{ins}/t_{ins}\ Btu/hr \quad .....(42)$$

$$q_{edge\ loss} = h_p\ (T_p - T_a)\ Btu/hr \quad .....(43)$$

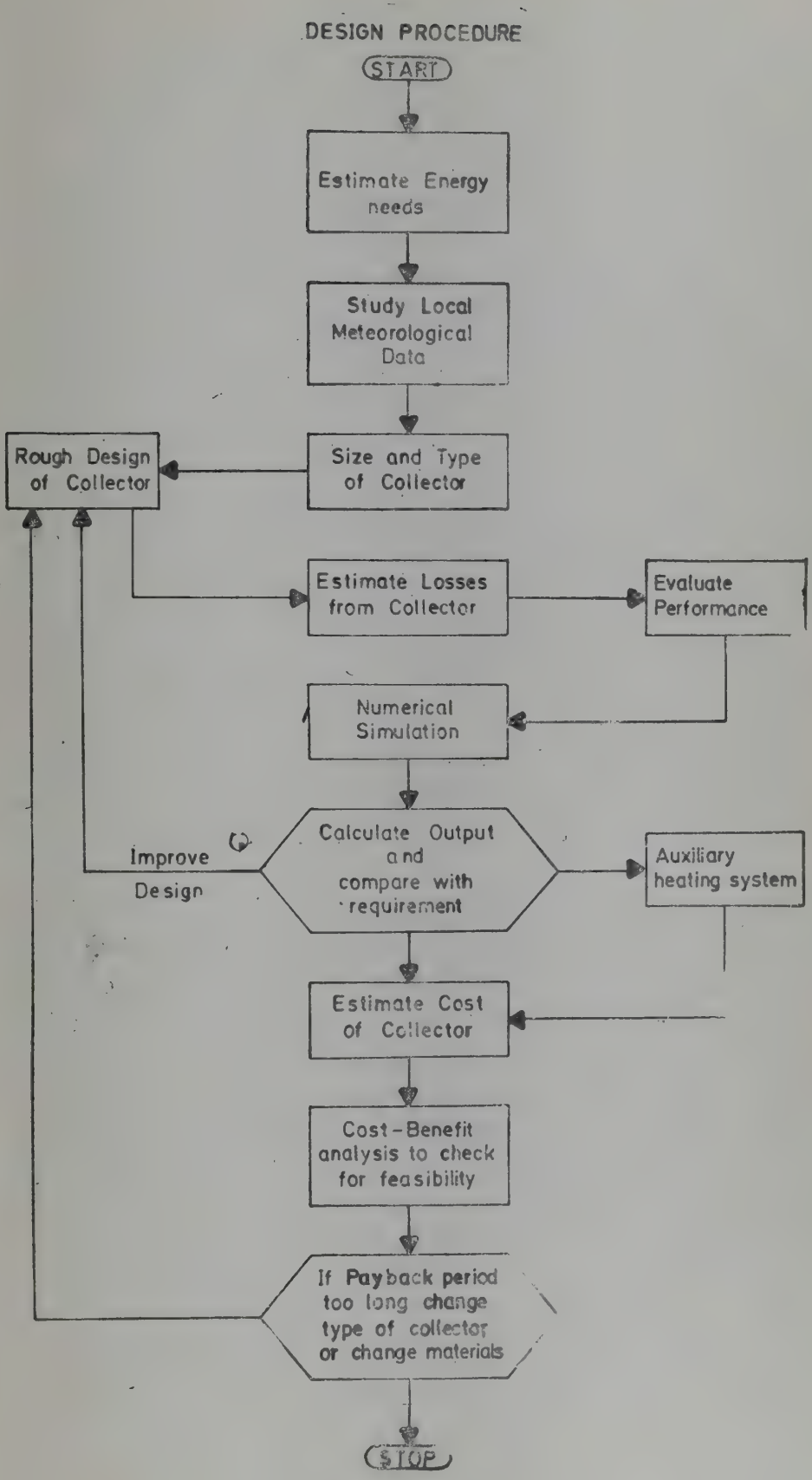
Here $N^* = 1.00$, 1.85 and 2.65 for one glass, two glass and three glass covers respectively, and

$$f^* = 0.9556 - 0.211\ h_w + [1.0 + \frac{N^* - 1}{N^* \times 3}\ ]\ h_w^2 \quad .....(44)$$

T_p and T_a are in°R, A_p is the outer perimeter area of collector and $h_w = 1.0 + 0.21\ V$ Btu/hr ft²°F and V is velocity of air in ft/sec.

$$\text{Now } U_L = \frac{q_t A + q_b A + q_{edge}\ A_p}{A\ (T^p - T_a)} \quad .....(45)$$

This first estimate is used to determine q_u, the useful energy collected by the collector, from which T_p is obtained With this preliminary design, a refined design, performance estimate, and cost estimate are made. Having obtained the cost estimate, a check is now made to see if the returns and pay back period are acceptable. If they are not acceptable,


DESIGN PROCEDURE
START
Estimate Energy needs
Study Local Meteorological Data
Size and Type of Collector
Rough Design of Collector
Estimate Losses from Collector
Evaluate Performance
Numerical Simulation
Calculate Output and compare with requirement
Improve Design
Auxiliary heating system
Estimate Cost of Collector
Cost-Benefit analysis to check for feasibility
If Payback period too long change type of collector or change materials
STOP

use of less expensive materials and an attendant reduction in performance and perhaps life are also indicated, and the cycle is repeated.

This procedure is indicated in the flow chart on page 87.

3.5.6. Circulation System

As indicated earlier, thermosiphon circulation is preferred for smaller units, while for large systems, forced circultion is preferred. If thermosiphon circulation is used, the size of the storage tank is chosen such that it stores anywhere from 1.5 to 2 times the daily water requirement. If an auxiliary heater is available, the size can be reduced. The storage tank is connected to the collector with the shortest possible lengths of large bore (15 mm or more) insulated pipes ; to prevent reverse flow, the bottom of storage tank is elevated by at least 0.6m, above the top edge of the collector.

Forced circulation is created by using a centrifugal pump which is sized to provide the desired flow, and develops a sufficient pressure head to overcome frictional losses.

The quality of water to be heated, i.e. whether it is acidic, basic or has salts and other corrosive or absorbing substances dissolved in it, is also an important consideration in the selection of the circulation system. If the water quality is too corrosive for the material of the collector, a two fluid loop containing a fluid which is benign to the collector material and which circulates the same fluid over and over again, through the collector, is used to heat it and then passed through a heat exchanger. The second fluid loop contains water (or any other fluid) which is corrosive or contaminated This fluid picks up its heat from the heat exchanger.

This double loop system would be more expensive, and incurs heat losses because of the heat exchanger. One of

the chief reasons, why copper collectors are very commonly used, even though copper is expensive, is the tolerance of copper to a large range of water quality. Aluminium, which has highly desirable properties, like excellent thermal conductivity, low density, good strengh, low cost, suffers from the fact that it is prone to rapid corrosion in even slightly alkaline water. While the performance of aluminium collectors is good, one is forced to use closed loop heating, with deionised water. Steel while having a little better corrosion resistance, needs special treatment and precautions before being used.

3.6. Problems, Prospects and Tasks

The flat–plate collector has been subjected to an extremely thorough analysis and study because it is by far the most commonly used technological convertor. But this does not automatically mean that no further work needs to be done on flat-plate collectors. There remains a large amount of work to be carried out before large scale deployment of solar collectors becomes a possibility. This is evident, when it is realised, that while solar radiation has been freely available all along, it has not been used technologically by man on any significant scale. Many of the problems are related to the cost of the collector. The collectors that are marketed are made from metal and glass, are very heavy (upto 50 kg/m^2) and equally expensive (Rs. 20 to 30/kg). It is apparent that economy can be achieved by substituting different lighter and/or less expensive materials, for the collector.

Reduction in cost can be achieved by reducing the weight. In the case of metallic collectors, there is a certain minimum thickness requirement, imposed either by corrosion in the metal or by hydrostatic pressure. If copper is used the wall thickness can be quite small, and just sufficient to withstand hydrostatic pressure. With steel it is otherwise. Hence, a systematic study of alternate materials, that perform satisfactorily is to be carried out.

The next set of problems relate to the durability or life time of collectors, i.e. ensuring trouble free functioning for a period long enough for the collectors to pay back the investment. However, cost and longevity are linked. Another problem area, is the lack of sufficient data on performance and utility, especially, under very cloudy conditions. System design, design and integration of auxiliary heating systems to solar heaters, storage of heat, and control systems are some of the other aspects that need further study. In addition to these, studies on optimisation of the collector and the entire system are also essential. Since any improvement leads to reduction in the collector area required and hence the cost, studies may be carried to improve the performance of collectors. Looking at these in a little more detail, we can see that there are a large number of very interesting and important investigations that still have to be carried out.

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4. A Critique of SPP Projects on Solar Energy

The SPP projects in the area of Solar Enegry have been very popular, as witnessed by the large number of projects carried out in the area, over the past five years. In the next chapter a review of each of these projects is given, to serve not only as a catalogue, but also to highlight both the good points and weaknesses in these projects. These project reviews give the title of the project, the objectives and approach, pertinent results, and a brief critique of the project. An examination of these reviews reveals that while there are a few very good projects, by far the majority of the projects can only be classified as ordinary. An attempt has been made here to identify what appears to be the main cause that has prevented these projects from doing better. Basically, it is essential to devote some attention to formulating the project. It may be necessary to carry out a fair amount of study before setting down the goals of the project, so that they are realistic, in the sense that given the constraints of time and facilities available, practically achievable-goals have to be specified. The importance of carrying out performance tests should never be forgotten. In fact this aspect has received the least attention in most projects. Also to be noted is that in many cases investigators have repeated work carried out by earlier investigators. While there is nothing wrong in attempting such projects, the objectives should be clear enough and cognizance should be taken of earlier work.

4.1 Student Project on Solar Cookers

Quite a large number of projects (as many as eight)

on solar cookers have been carried out in the past five years. While some of these projects have partially fulfiled the objectives listed in them, many have not been able to progress beyond a preliminary stage. It is evident, that the project gcals are too ambitious, and both the time and facilities availble do not permit satisfactory completion of the projects.

In India a very large fraction of the energy consumed in the domestic sector goes towards cooking and water heating. With widespread use of cooking fuels like firewood, and the attendant high cost, it is evident that once an effective solar cooker becomes available, it will find a large application. In spite of this situation good cost effective and acceptable cookers are not yet available. Since the principals involved in the design of solar cookers are quite well known, [1], the problems in making an effective solar cooker lie in the design and fabrication of the cooker. The objectives of the student projects carried out, are ineed laudable, since they primarily deal with design and farbrication. They have not really suceeded in testing out the consequences of their design. Unless design is tested and examined properly, its effectiveness cannot be proved. Thus, it is absolutely essential that each design concept is tested thorughly. The discrepencies between the designed and the actual performance can result from many reasons. Usually the design is based on a steady state anaysis while in actual cases the solar, influx is changing with time. Imperfections in fabrication, lack of precise data regarding the properties of material utilised in fabrication, are some of the reasons behind these discrepencies.

Let us consider specific cases. The idea of using heat pipes in conjunction with solar cookers is excellent, in as much as heat can be carried from the solar collector which is necessarialy to be kept outside, to the kitchen.

An attempt to carry out a project where design and fabrication of all components is involved-, the solar collector (essentially a parabolic dish reflector and absorber or some equivalent unit), the tracking unit (if a parabolic cylinder or a flat-plate collector is used tracking is not essential), and the heat pipe, is bound to end up partially complete, because each of the components require full attention, before they can be success fully designed and fabricated. Separate projects, for example, one dealing only with design and development of solar concentrators, the design and development of a tracking unit for the concentrators as a second project, and the design and development of a heat pipe as a third project, should be carried out, either sequentially or in parallel by different groups over a period of time. Another project for integrating these would then yield meaningful results. It can also be kept in mind that these separate projects do not have to use the sun as the source of energy, for example, electric heaters can simulate the heat source for the evaporator of a heat pipe. This task could be accomplished in the following manner : A project once started could be continued by successive batches of students, each batch analysing a part of the overall problem.

Another commonly observed result is that the peak temperature reached in the cookers is rather low, except in a few cases. This is because the losses are too high. Provisision of adequate insulation at the bottom, proper sealing of glass cover so that there is no leakage of air in the collector box, provision of two layers of glass, allowing the material to be cooked for long enough time, use of the right kind of paint (black board paint is inexpensive and effective), correct orienatation of the box, are some of the most obvious corrective measures. Furtner

more, when efficiencies are cited or experiments are conducted, it is necessary to know the amount of solar insolation on the collector. For this either an inexpensive photocell (or more accurate meter) or values computed for the locale is to be utilized.

4.2. Solar Driers

Eleven different projects, dealing with, driers for agricultural produce, and the regeneration of an absorbent (silica gel) of a dehumidifier have been carried out. It is noteworthy that in several instances work initiated in one year has been continued in the next year. It is also to be noted that a fairly large number of tests have been carried out on these driers.

Drying or removal of moisture from a porous medium is a fairly complex process, as it involves several steps such as; removal of moisture at the surface through evaporation, and diffusion of moisture from the interior to the surface. The evaporation at the surface is accomplished by maintaining a sufficiently large difference in the partial pressure of water vapour at the surface of the product to be dried and that of the air surrouding it, by forced convection. So both heat and high velocities are essential for quick drying.

In many of the projects carried out it appears that the solar collector has not been constructed for optimal performance. For effectively heating air, there should be a sufficient area of contact between the collector plate and the air and multiple passes may be necessary to raise the temperature of air to a higher level. Provision of adequate insulation on the collector and ducts, use of glazing, proper channelling of air in the collector have to be ensured. The distribution of hot air over material to be dried is

another aspect that needs quite a lot of attention, so that adequate surface area of the material being dried is exposed to the hot air. Within the drier cabinet, the distribution of air and grain plays an important role in determining the effectiveness of the drier. The use of blower becomes necessary when large installations are involved. Here the pressure drop across the collector and drier has to be reduced for reducing the blower capacity. Efforts must be made to evaluate this parameter in all the projects. When evaluating the efficiencies it is to be borne in mind that the actual solar insolation falling over the collector is to be used (either by measuring or calculating it).

These projects can also benefit if the two components : the solar air heater and the grain silica gel drier are studied separately, and each one tested separately to study their relative performance. Hot air to the drier could be directly supplied by installing an electrical heater in the air stream from the blower. The solar performance could be checked separately for different air flow rates. The primary objective should be to compare the performance of the fabricated devices with the performance predicted on the basis of the analysis.

4.3. Solar Water Heaters

Only 4 projects dealing with solar water heaters have been carried out–this smaller number probably reflects the feeling that simple water heaters of the flat–plate type are well understood and further work in this area may not be funded. The projects undertaken here, have very clear objectives – fabriacting and testing inexpensive solar heaters, but a sound basis in the design and fabrication of the experimental set up would enhance the quality of the project. If the objective is clear, as for example the determination of the optional depth of

water to be used in a solar tank type heater, an analysis (even if it is a simple first order crude analysis) has to be made to derive the basis for choosing a particular depth (in this case, the thermal mass or volume and the surface area available for heating, etc.), The effect of different insulation materials could also be analysed. After these improvements are made, the experimental parameters can be chosen with a good underlying rationale instead of being chosen at random.

Another aspect that has to be kept in mind is that when comparisons are made the test conditions should be as nearly identical as possible.

A general remark which applies to most projects is that the goal that one has to have in mind, in carrying out a design, and later, fabrication and testing of the device, is to understand how well one can carry out a design from first principles. If there is a large discrepancy between the expected and actual behaviour, the investigators should analyse, why this has occured and then use this knowledge to refine the design procedure.

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5. Review of SPP Projects on Solar Energy Devices

5. 1 SOLAR COOKERS

5.1.1 College : KREC, Surathkal

Project : Solar cooker using heat pipe

Year : 1978–79

Objectives :

To construct a solar cooker using a parabolic concentrator and heat pipe.
(An experimental unit was designed to investigate the possibility of using a heat pipe in conjunction with a collector, for cooking purposes).

Specifications :

The device is not designed for a specific capacity. The collector is of the paraboloidal type having an area of 26793.85 cm^2 and a focal length of 20cm. The heat pipe is made of galvanised iron and has a diameter of 10 cm and length of 45.0 cm.

Performance Figures :

The experimental set-up consists of a paraboloidal focussing collector to focus solar radiation onto the top of a vertically placed heat pipe. The lower end of the heat pipe is immersed in water through which a continuous flow is maintained. Tests were conducted to evaluate the performance of the collector and that of the heat-pipe.

A. **Collector performance** :

Tests conducted on 15-5-79
Duration–8 hours (from 8 a.m. to 4 p.m.)
Maximum temperature – 99°C at 1-30 p.m.
Average temperature – 96°C.

B. **Heat pipe performance** :

B. 1. Heat pipe with foam wick : Tests on 20-5-79
Duration : 5 hours (from 11 a.m. to 4 p.m.)
Working fluid – water
Pressure inside the tube – 0.3 kg/cm^2
Water flow rate – 0.5 litre/minute
Rise in temperature of water – Nil
B. 2. Heat pipe with wick (foam) – Tests on 25-5-79
Working fluid – Kerosene
Pressure – 1 atmosphere
Duration – 4 hours (from 11. a.m. to 3 p.m.)
Water flow rate – 0.5 litre/minute
Rise in temperature of water – Nil
B. 3. Heat pipe with pebbles – Tests on 11-6-79
Duration – 8 hours (from 8 a.m. to 4 p.m.)
Rate of flow of water – 0.5 litre/minute
Rise in temperature of water – 23°C
Average rise – 18 °C
Max. temperature at outlet – 61°C
Temperature at the inlet – 38°C
(Efficiency 40–45%)

Technological Innovations :
In this project, an attempt has been made to transfer heat from the focus of the collector to the water using a heat pipe. The heat pipe is a hollow tube closed at both ends with an inner porous lining or a wick which is used to rain a working fluid by capillary action. The tube is held in a vertical position and the upper end is heated by solar radiation. This evaporates the working fluid. Vapours of the fluid are cooled at the other end of the tube, which is kept inside a water bath (in the heat tube filled with pebbles).

Comment :

1. The maximum temperature obtianable with the device is about 61 °C which makes the device unsuitable for cooking purposes.

5. 1. 2. College : RVCE, Bangalore

Project : Solar Heat Pipe cooker

Year : 1979-80

Objective :

To fabricate and test an absorption type solar cooker (solar steam cooker.)

Specification :

Area of the collector plate = 1.5 × 0.5 = 0.75 m^2

The cooker has not been designed for any specific capacity.

Performance Figures :

The cooker consists of (i) a tube and plate type flate-plate collector and (ii) a steam cooker. An aluminimum sheet is used as the absorbing material. The sheet has a serpentine grove into which a copper pipe is inserted. The heat abosorbed by the aluminium sheet is transmitted to the copper pipe. The collector is connected by means of G. I. piping to the steam cooker. When the collector is exposed to solar radiation, water placed inside the copper tube vapourises. The steam thus produced is used for cooking the food in the cooker.

Performance tests gave the following results :

Maximum temperature of water in the copper tube–98°C

Maximim temperature of water in the cooker–65° C

Ambient temperature – 30°C

Technological Innovation : Nil

Comments :

1. The temperature inside the cooker is not sufficient for cooking purposes. (The temperature for cooking should be around 100-120°C).
2. The cost of the unit is about Rs. 600/-, which is too high. (A typical figure would be in the range of Rs. 300/–only.)

5.1.3. College : JCE, Mysore

Project : Fabrication of heat pipe type solar cooker

Year : 1979–80

Objective :

To construct a solar cooker.

Specifications :
Size of collector plate = 1.22m × 1.52m.
Aluminium tube diameter = 1.9 cm
Length = 1.83 m
Cooker capacity = 1 litre

Performance Figures :

The cooker consists of (i) a tube and plate type flat-plate collector and (ii) a steam cooker. The collector uses an aluminium sheet as absorber. The sheet has a longitudinal groove into which an aluminium pipe is inserted.

Experiments on the cooker gave the following results :

A. Maximum water temperature (without glass cover) = 79°C
   Maximum temperature = 95°C

B. Experiments on collector – cooker combination
   Water temperature in the cooker = 70°C

Technological Innovations : Nil

Comments :

1. The temperature inside the cooker is about 79°C, which is too low for cooking purposes. (For cooking, the temperature should be 100 – 120°C).
2. The cost of the device is high (about Rs. 600/–).

5.1.4. College : BVBCE, Hubli

Project : Solar cooker

Year : 1978–79

Objective :

To design and fabricate a reflector type solar cooker.

Specifications :

Projected area of the aperture = 1.54 m^2

Time for bringing 4 liters of water from 25°C to 100°C under clear sky conditions = 28 minutes (in the month of February)

Efficiency – 85%

Methodology :

1. A detailed study was made of different solar energy devices.
2. Different types of solar cookers were examined and their functioning analysed. The cookers studied include a solar heat box, solar cooker, solar oven, reflecting type solar cooker and storage type cookers. Advantages and disadvantages of these cookers were also looked into.
3. A reflecting type cooker was designed and fabricated.

Description of the Equipment :

The cooker is of the direct heating reflector type, i.e., the solar radiation on plane mirrors is reflected on to the cooker surface. The reflector surface is constituted of 18 plane mirrors, arranged in the from of frusta of two cones having different apex angles (the apex angle of the upper cone is smaller than of the lower cone). The mirrors are supported on a plywood framework. The assembly of mirrors is supported on a tripod stand which can facilitate a few degrees of manual tilting to capture maximum radiation. The cooker is suspened at the focus of the mirror assembly. The cooker consists of two vessels, placed one inside the other with an annular space in between. The annulus is filled with water. When the device is exposed to solar radiation, the mirrors focus the radiation into a cooking vessel. Water in the annular space is converted to steam and cooks the food placed in the inner vessel.

Performance Figures :

No performance studies have been carried out on the cooker.

Comment :

1. The cooker is expensive (costs about Rs. 950/–). The major items which contribute to the cost of the cooker are plane mirror strips (about Rs. 550/–) and plywood strips (Rs. 120/–).

5.1.5. College - BEC, Bagalkot

Project : Solar cooker

Year : 1979–1980

Objective :

To design and fabricate a solar cooker.

Specification :

The cooker uses a convex lens made of acrylic sheets.
Diameter of lens = 80 cm
Focal length of lens = 200 cm

Methodology :

1. Availability of solar energy and the prospects for its utilization, were studied.
2. Different types of cookers and their functioning were examined.
3. A focussing type of solar cooker using an acrylic lens was designed and fabricated.
4. Tests were conducted to evaluate the performance of the cooker.

Description of Equipment :

The cooker uses an acrylic lens to focus a beam of light onto a cooking vessel placed at the focus of the lens. Acrylic sheets were first moulded into the form of a lens and water was filled in the space in between. A wooden stand was constructed to hold the lens. A cooking vessel made

of sheet metal was placed in a wooden box filled with saw dust and the whole assembly was placed at the focus of the lens.

Performance Figures :

Experiments were conducted to :

1. Trace the focal point,
2. Measure the temperature at the focus,
3. Measure the temperature of 5 litres of water placed in the cooking vessel.

The temperature at the focus was measured using a chromel–alumel thermocouple. The maximum temperature at the focus was found to be about 425°C.

In another experiment, 5 litres of water placed in the cooking vessel, was heated to 84°C from 29°C in about $3\frac{1}{2}$ hours. (Efficiency 27%).

Attempts to cook rice were unsuccessful as the temperature did not reach 100°C.

Comments :

1. The cooker has a low efficiency. The temperature of water in the cooking vessel does not reach 100°C. Hence it is not actually possible to cook food stuff.
2. The cost of the cooker is very high (around Rs. 2000/–). The main item contributing to the high cost is the lens (cost around Rs. 900/–)

5.1.6. College : JCE, Mysore

Project : Utilisation of solar energy and fabrication of solar cooker.

Year : 1979–80

Objectives :

1. To fabricate and test
   – a parabolic trough solar cooker (reflector surface made of aluminium foil)

– a parabolic trough solar cooker (reflecting surface lined with mirror strips)
– a sun basket cooker (paraboloid reflecting surface).

Specifications :

1. Parabolic trough cooker – cost Rs. 2081/–
   (reflecting sheet type)
   Surface area normal to solar radiation = 0.945m^2.
   The focus is 10 cm from the apex.
   Parabolic reflector surface obeys the equation $y^2 = 4ax$
2. Parabolic trough cooker using mirror strips — cost Rs.3631/–
   Area normal to solar radiation = 0.72 m^2
   Equation of the parabolic profile is $y^2 = 160x$
   The focus is 40 cm. from the apex
3. Sun basket – cost Rs. 140/–
   Paraboloid reflecting surface
   Area presented to the solar radiation = 3.14 m^2

Methodology :

1. The availability of solar energy and its utilisation prospects were studied.
2. The different methods of converting solar energy into a useable form were also studied, these include chemical conversion, electrical conversion and thermal conversion.
3. Flat – Plate and focussing type of collectors were examined in detail.
4. Three different types of solar cookers were fabricated and tested.

Description of Equipment :

1. Parabolic trough cooker (reflecting sheet type).
   A parabolic trough reflector covered with aluminium foil focusses the incoming solar radiation onto a metal tube containing water. Water is converted into steam and enters a cooking vessel in contact with the metal tube, thus heating the contents of the vessel.

2. Parabolic trough cooker (reflecting mirror type).

   This cooker is similar in all respects to the parabolic reflector cooker, except for the reflecting surface which is lined with mirror strips.

3. Sun basket.

   A paraboloid reflecting surface focusses the incoming radiation onto the cooking vessel placed at the focus. The paraboloid is made of 'paper mache' pulp and the inner surface is covered with aluminium foil.

Performance Testing :

1. Paraboliod reflecting sheet type cooker ;

   Efficiency of concentrator = 60%
   Cooker efficiency = 76%
   The cooker can cook 0.5 kg of rice in 30 minutes, 0.5 kg dal in 60 minutes and prepare 6 cups of coffee in 12 minutes.

2. Parabolic reflecting mirror type cooker :

   Efficiency of concentrator = 65%
   Cooker efficiency = 76%
   The cooking time for 0.5 kg rice is 25 minutes, for 0.5 kg dal 40 minutes, and for 6 cups coffee 7 minutes.

3. Sun basket :

   Cooking time for 0.5 kg rice is 30 minutes, for 0.5 kg dal 45 minutes, and for 5 cups coffee 5 minutes.

Comment :

1. Test have not been canducted to find out the overall efficiency of the cookers. (This is necessary because some of the efficiency values shown above have been arrived at theoretically and no experiments have been conducted to get the actual efficiency values.)

5.1.7. College : MCE, Hassan

Project : Solar cooker and water heater

Year : 1978–79

Objective :

To design and fabricate (i) a solar cooker and
(ii) a solar water heater.

Specifications :

1. Solar cooker : The cooker has been designed to bring 1 litre water from 30°C to 100°C in 15 minutes, The projected area of the parabolic reflector = 0.78m^2.
2. Solar water heater : The solar water heater has been designed to bring the temprature of water flowing in a pipe at the rate of 38 litres/hour from 30°C to 70 C. Project area of the reflector = 4.2m^2.

Methodology :

1. Different methods of converting solar energy into a unstable form, and the methods of storing the solar energy were discussed.
2. Flate-plate and focussing collectors were studied.
3. A solar cooker and a water heater were fabricated and tested.

Description of the equipment :

1. Solar cooker : The cooker uses a parabolic reflector. The reflector is made of mild steel and its inner surface is glued with anodised aluminium sheet. The paraboloidal reflector reflects the incident radiation onto a cooking vessel placed at its focus. The vessel is coated with black paint for maximum solar energy absorption.
2. Solar water heater : The heater uses a channel of parabolic cross-section lined with anodised aluminum sheet to serve as reflecting surface. It focusses all the radiation incident on it, onto an aluminium pipe placed along the focus of the channel, water flowing in the aluminium pipe gets heated by absorbing solar radiation.

Performance Testing :

No performance figures have been presented.

Comments :

1. As no performance figures have been presented, it is difficult to say whether the units work satisfactorily or not.
2. The cost of the cooker is high (Rs. 600/–). This is mainly due to the fact that the paraboloidal reflector has been made of mild steel and anodised aluminium sheet.

5.1.8. College : BDT, Davangere

Project : Performance study on solar cookers

Year : 1981–82

Objective :

To carry out performance studies on three solar cookers designed and fabricated at BDT, Davanagere.

Specifications :

Cooker 1 : (Hot box type cooker without a reflector)
(cost Rs. 603/–)
Box dimensions—52 cm × 53 cm × 30 cm
Basal area—52 cm × 52 cm

Cooker 2 : (Hot box type solar cooker with a single reflector)
(cost Rs. 621/–)

Box dimensions—52 cm × 52 cm × 30 cm

Basal area—52 cm × 52 cm

rea of the reflector—52 cms × 52 cms

Cooker 3 : (Hot box type cooker with many reflectors)

Box dimensions— 52 cm × 52 cm × 25.5 cm

Basal area—52 cm × 52 cm

The cooker uses 8 reflectors

4 reflectors of square shape (52 cms × 52 cms)

4 reflectors of triangular shape (base 18cms and height 25cms)

Methodology :

1. Different types of solar cookers were studied. The advantages and limitations of different cookers were discussed.
2. Keeping in mind the cost and ease of fabrication, three hot box type solar cookers were fabricated and their performance evaluated.

Description of Equipment :

Cooker 1 : The cooker employs an insulated wooden square hot box with blackened metal lining inside (basal area 52cm × 52 cm) and a single glazing at the top. The cocker does not make use of a reflector.

Cooker 2 : The cooker uses an insulated wooden box of square shape with blackened metal lining inside (basal area 42 cm × 42 cm) and single glazing at the top. The cooker uses

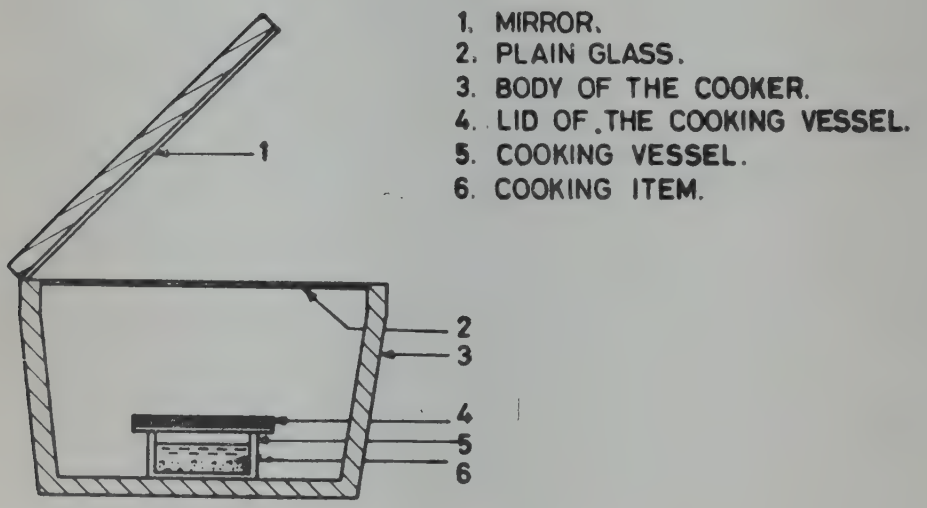

Fig. 5.1 Solar Cooker

a plane silvered glass reflector (42cm x 42cm) (see fig. 5.1).

Cooker 3 : This cooker employs an insulated cardboard box (42 cm x 42cm x 24.4 cm) which has no glazing at the top. The cooker uses eight reflectors, made of Mylar sheet, four of a square shape (42 cm x 42 cm) and four of a triangular shape (width 18 cms. and height 24 cms.)

Tests were conducted in the months of June and July 1982. The results are tabulated below.

Date and period of experiment	Cooker 1 [Max. Temp. inside the cooker °C]	Cooker 2 [Max. Temp. inside the cooker °C]	Cooker 3 [Max. Temp. inside the cooker °C]
27–5–82 (0930–1445H)	90	98	66
28–5–82 (1445–1645H)	64	70	50
29–6–82 (9–113H)	85	90	51
2–7–82 (15–1654)	65	73	53
6–7–82 (1445–19H)	63	69	52
Efficiency :	18%	20%	12%

About 1 litre of water was placed in the cooker for most of the experiments.

Comments :

1. All the 3 cookers have very low efficiencies. Cooker 2, which is supposed to be the most efficient, has an efficiency of only 20%. Cooker 3 attains temperatures of the order of 65°C and therefore it connot be used for cooking purposes.

2. Costs of cooker 1 and 2 are high. Cooker 1 costs about Rs. 600/– and cooker 2 costs about Rs. 621/–.

5.2. SOLAR PADDY DRIER

5.2.1. College : P.E.S.C.E., Mandya

Project : Utilisation of Solar Air Heater for Drying Agricultural Produce

Year : 1978–79

Objective :

To design and fabricate a solar drier for drying agricultural produce.

Specifications :

1. The drier is designed to deliver 478.08 kg. of air per day at a temprature of 54°C.
2. Area of the collector box = $1m^2$
   Efficiency = 41.5%

Performance Figures

The drier consists of an absorber (which is nothing but a flat-plate collector suitably modified to heat the air) and a drier bin. A hand blower delivers air to the absorber which in turn is connected to the drier bin. Tests were conducted on the 23rd and 24th of July 1979. In these tests, a known weight of paddy was kept in the drier bin and air was blown through the bin for a specified period. The results are as flows :

Date	Average air outlet tempera-ture (°C)	Air inlet tempra-ture(°C)	Duration (minutes)	Initial paddy wt. in kg	Final wt.
23-7-79	52°C	32°C	90	10	9.74
24-7-79	50°C	34°C	60	10.3	10.1

Technological Innovations : Nil

Comments :

1. A blower should be used to supply air to the absorber. This necessitates the use of an auxiliary source of power.

2. The absorber and drier bin are made of teak wood. This increases the cost of the equipment. The glass cover may be replaced by PVC sheets. This reduces the cost.

5.2.2 : College : RVCE, Bangalore

Project : Solar Paddy Drier

Year : 1978–79

Objective :

To design and fabricate a solar paddy drier.

Specifications :

1. The drier is designed to dry 100 kgs of grain per day (moisture content reduction 9.14%).
2. The collector area is 3.7m^2
   (efficiency about 39%)

Performance Figures :

The drier consists of collector (air heater), a blower and a bin connected in series. Performance tests were conducted in the month of June. About 20kgs of paddy was placed in the drier bin and hot air was blown through the bin for about an hour. The results are as under.

The maximum temperature of air at outlet of the collector (with grains) was found to be 57.7°C and the temperature, without grains, was found to be 72°C.

The time required to reduce the moisture content of 20 kgs of paddy from 25% to 11% was found to be about 1 hour.

Technological Innovations :

The collector uses a corrugated G. I. Sheet as the absorber. Air is made to pass on both sides of the absorber. This arrangement increases the efficiency of the drier.

Comments :

1. The drier uses a blower which necessitates the use of an auxiliary source of power.
2. The glass sheet increases the cost of the drier. Cost reduction could be achieved by replacing the glass sheet by PVC sheets.

5.2.3. College : KREC, Surathkal

Project : Solar Paddy Drier

Year : 1978–79

Objective :

To design and fabricate a solar paddy drier.

Specifications

The drier is not designed for a specific capacity. The collector area is 1.6m^2.

Description of Equipment :

The drier makes use of a collector and a drying bin. The collector uses a galvanised iron sheet as an absorber. The absorber is provided with fins on one side and air is passed on that side only. The collector is connected to a drier bin capable of holding 30 kg. of paddy. An electrically driven blower supplies air to the collector.

Performance figures :

Outdoor tests were conducted on the 24th, 25th of April and on the 20th of May. A Sol-A-meter was used to measure solar insolation. Tests were conducted :

1. To determine the variation of collector efficiency with respect to time :
2. To determine the variation of air temperature at the collector outlet with respect to time ;

3. To determine the loss of moisture with the passage of time, for a known quantity of paddy.

Date	Solar insola-tion [W/m²]	Max. temp. obt. °C	Eff. %	Max. temp. rise °C	Outlet temp. °C	Effi-ciency %
23–4–79	3465.7	62 [1300H]	51.6	26.5 [1300H]	53 [min] [1600H]	77.8 [Max]
25–4–79	3938.2	56.5 [1300H]	33.8	—	50.52 [1600H]	46.2 [Max]
20–5–79	3211.5	61	41.5	—	52 [1600H]	65.7 [Max]

Tests on 25–5–79

(i) Weight of paddy = 5 kg

Moisture reduction = 14% in a duration of about 1 hour

Moisture reduction = 17% duration 2 hours

(ii) Weight of paddy = 10 kg

Moisture reduction = 14% in about 2 hours

Moisture reduction = 17% in about 3 hours

The results clearly indicate that as the weight of the paddy increases, the time required to reduce the moisture content by a given amount also increases.

Technological Innovations : Nil

Comments :

1: The drier uses a blower. This necessitates the use of an auxiliary power source.

2. The drier can dry about 40 kgs of paddy per day. For a collector area of 1.6 m², the quantity of paddy dried is quite low (in other words the efficiency of the drier is low).

5.2.4. College : BVBCE, Hubli

Project : Solar Grain Drier

Year : 1977-78

Objective :

To design and fabricate a solar grain drier.

Specifications :

Collector area = $2m^2$ (2m × 1m)
Blower capacity = $1.4m^3$/min (about 1.54 kgs/min)
Air temperature at the outlet = 60°C
Air temperature at the inlet = 28°C
Collector efficiency = 65%

Methodology :

A study of the availability of solar energy was initially made. Different devices utilising solar energy were then studied. The possibility of using solar energy, with the specific purpose of drying seeds in rural areas was also examined. Advantages and disadvantages of various methods of drying were looked into. Based on these studies, an indirect air heater type of grain drier was fabricated.

Description of Equipment :

The drier consists mainly of (i) a collector (air heater,) (ii) a blower and (iii) a drier bin connected in series. The collector is made of a wooden box insulated on all sides and covered with a glass sheet at the top. It uses a finned G. I. sheet as the absorber. Air for drying is supplied by the blower. The grain is placed in the bin and hot air from the collector is passed through the bin.

Performance Figures

Performance studies were not conducted.

Comments :

1. The unit uses a blower which necessitates the use of an auxiliary source of energy other than solar energy. The blower also increases the cost of the unit.

2. The unit costs about Rs. 2,700/–. Small farmers cannot afford the unit.

5.2.5. College : BMSCE, Bangalore

Project : Solar Grain Drier

Year : 1978–79

Objective

To design and fabricate a solar grain drier.

Specifications :

Area of collector = 4.45 m^2
Bin dimensions = (91.4 cm × 91.4 cm × 91.4 cm)
(capable of holding about 150 kgs. of paddy)
Blower capacity = 8.75m^3/min.

Methodology :

1. A study of the availability of solar energy was initially made.
2. Different devices used to exploit solar energy were studied.
3. Various types of collectors-flat–plate collectors, focussing collectors, honeycomb collectors, evacuated collectors and Fresnel collectors were studied.
4. Various methods of grain drying and their relative merits were discussed.

Description of Equipment :

The drier consists of a flat–plate collector, a blower, and a drying bin forming an open loop system. The collector is a wooden box covered with a glass sheet at the top. A black painted G. I. sheet is used as an absorber. The blower is electrically driven by a 3 -phase induction motor. The bin is made of G. I. sheet and holds the grain.

Performance Figures :

Experiments were conducted between 23 April 1979 and 28 April 1979. Paddy soaked in water for about 24 hours and dried for about 6 hours have been used for the experiments. The results are presented in a tabular form.

Comments :

1. The unit uses a blower which necessitates the use of an auxiliary source of energy. The blower increases the initial cost and the running cost of the unit.
2. The efficiency at low air flow rates is very low.

College : SIT., Tumkur

Project : Solar Paddy Drier

Year : 1978-79

Objective :

To design and fabricate a solar paddy drier.

Specifications :

Collector area $= 1.8m \times 0.9m = 1.62\ m^2$

The drier has been designed to reduce the moisture content of 20 kg. of paddy by 14% (from 35% to 11%)

Air temperature rise $= 26°C$

Air flow rate $25m^3/hr.$ (Efficiency = 22%)

Methodology :

1. A study of the availability of solar energy was initially made.
2. Different types of collectors such as flat-plate collectors and focussing collectors were then studied.
3. The possibility of utilising solar energy for grain drying applications was examined. Different driers in use (tray driers, continuous drier and through circulation driers) were studied.

4. A tray drier was then fabricated.

Description of Equipment :

The main components of the drier are a blower, the collector and a drier bin, all connected in series. The blower blows air through the collector G. I. pipes into drier bin. The collector is a wooden box covered at the top with a glass sheet. A black painted cor.ugated G. I. sheet serves as an absorber. Air flows through G. I. pipes placed under the corrugated G. I. sheet. The drier bin is an air tight chamber. The trays placed in the chamber one above the other, hold the grain.

Performance Figures :

Experiment conducted on 6-7-79
Weight of paddy = 20 kgs
Rise in temperature of air = 19°C
Collector inlet temperature = 29°C
Collector outlet temperature = 48°C
Time taken for drying 20 kgs of paddy = $1\frac{1}{2}$ hours
(Efficiency = 16%)

Comments :

1. The cost of the unit works out to be Rs. 2000/-. The major items which contribute to the cost are the blower and the G. I. pipes. The electrically driven blower increases the running cost.

2. The efficiency of the units is very low.

5.2.7. : College : BDTEC., Davangere

Project : Comparative Study of 2 Solar Paddy Driers

Year : 1980-81

Objective :

To compare the performance of two solar paddy driers designed and fabricated at the BDT Engineering College.

Specifications :

Air heater 1 : Collector area = 3.53 m^2
(collector has glass cover)

Air heater 2 : Collectr area = 4.675m^2
(collector does not have glass cover)

Methodology

1. The availability of solar energy was studied. Different methods of measuring solar radiation were discussed.
2. Various types of collectors, such as flat-plate collectors honeycomb collectors, evacuated collectors, Fresnel collectors, and focussing collectors, were studied.
3. The possibility of using solar energy for grain drying was examined in detail. Advantages and disadvantages of different methods of drying were looked into.
4. After considering the various parameters influencing the drier characteristics, two driers were fabricated.
5. Tests were conducted to study and compare the performances of the two driers.

Description of Equipment :

The main components of driers are a flat-plate collector, a blower and a drier bin, all connected in series. The flat-plate collector uses a black painted, corrugated G. I. sheet as an absorber. The two driers have collectors of different areas. One of the driers which uses the collector of smaller area, is covered with a glass sheet, whereas the collector of the other drier has on glass cover. The blower in both the driers draw air through the collector and delivers it to the drier bin.

Performance Figures

Drier 1 :
Area of the collector = 3.53 m^2 (with cover glass)
Wt. of paddy = 20 kgs

Experiment conducted on	Duration of test (Hours)	Rise in temp.of air °C	Volume flow rate m^3/min	Reduction in Moisture content %	Efficiency (%)
29.6.1981	4.5	11.0	1.56	8.5	15.0
30.6.1981	4.5	13.0	1.56	20.0	18.0
1.7.1981	2.5	11.5	1.56	16.0	24.0
2.7.1981	2.5	15.0	1.41	6.0	20.0
2.7.1981	1·5	11.0	1.41	2.0	20.0
Drier 2 :					
3.7.1981	6.5	14.0	1.56	23.0	20.0
4.7.1981	7.5	14.0	1.56	25.0	17.0
6.7.1981	5.5	17.0	1.41	16.0	21.0

Area of the collector = 4.675 m^2 (without glass cover)
Wt. of paddy = 40 kgs

Comments :

1. The efficiencies of both the driers are low.
2. Different weights of paddy have been used for the two driers. The tests should have been conducted using the same weight of paddy.
3. It has been claimed that the total cost of drier-2, works out to be lower than that of drier–1. However, the exact details regarding the total costs of the driers have not been presented in the report.

5.2.8. College : SIT, Tumkur

Project : Performance Study of a solar paddy drier

Year : 1979-80

Objective :

To evaluate the performance of a solar paddy drier designed and fabricated at SIT, during 1978–79.

Specifications :

Collector area = 1.62m^2

The drier has been designed to reduce the moisture conent of 10 kgs of paddy from 35% to 14%.

Air temperature rise = 26°C

Air flow rate = 25m^3/hr (efficiency = 22%).

Methodology :

1. The possibility of utilising solar energy for different applications was examined.
2. Various types of collectors were studied. These include flat-plate collectors, flat-plate collector with booster, focussing collector, concentrating collector and collector with selective coatings.
3. The solar paddy drier constructed during the year 1978-79 was suitably modified and its performance evaluated.

Description of Equipment :

The drier consists of a blower, a flat-plate collector and a drier bin, all connected in series to form an open loop. The blower forces air through the G. I. pipes in the collector, into the drier bin. The collector G. I. pipes are placed under a corrugated G. I. sheet (absorber) which is painted black for maximum absorption of solar radiation. The drier bin is an air tight chamber with two trays placed one above the other. The trays hold the grains.

Performance Figures :

Experiment No.	1	2	3
Weight of paddy dried	11.5 kg	20.75 kg	41.5 kg
Duration of test	90 min.	90 min.	90 min
Air temperature at inlet	32°C	38°C	38°C
Max. temp. of air at outlet	80°C	79°C	59°C
Moisture content reduction	0.24%	1.14%	5.5 %

Comment :

1. The efficiency of the drier is very low. This may be due to a very low rate of air flow. Some more tests have been conducted by increasing the air flow rate.

5.2.9. College : BMS Evening College, Bangalore

Project : Design, fabrication and performance evaluation of a solar drier

Year : 1980–81

Objective :

To design, fabricate and evaluate the performance of a passive type solar drier for agricultural produce.

Specifications :

Collector area = $1m^2$

Maximum moisture content that can be removed per day = 3.2 kg

Effciency = 50%

Methodology :

1. A brief survey of the availability of solar energy and its utilisation was carried out.
2. Different types of solar driers were studied and their drawbacks discussed.
3. A low-cost, passive type solar drier was fabricated and tested.

Description of Equipment :

A flat–plate collector is used in conjunction with a vertical cabinet, to provide a thermoszphon or chimney effect. The drier essentially consists of a flat–plate collector, drying chamber, storage trays and chimney with a flap flow regulator. The flat–plate collector is of size 1.48m X 0.67m. The

collector uses a G. I sheet painted black, as an absorber. The collector is inclined at an angle of 13.5° to the horizontal and it is covered with a transparent material to cut down convection losses and to provide a ''Green House Effect.'' The collector communicates with a vertical rectangular drying chamber of size 75cm x 40cm x 80cm. The chamber receives heated air from the collector side of the drier and the exhaust is through the chimney. The chamber houses four trays containing the products for drying. The trays are of drawer type with their bottom covered with wire mesh. Wire mesh allows the heated air to pass through the products kept on the trays for drying. The bottom of the drier is kept open as it was intended to place the drier directly on the floor.

Performance Figures :

Extensive field tests were conducted to study and evaluate the performance of the drier. The experimental details and the results are as follows :

Experiment 1 : Initially, the drier was loaded with 960gms of grapes to find out the moisture removing capacity of the drier. In about 11 hours, about 99 gms of moisture were removed. The average rise in the temperature of the air was found to be 14°C.

Experiment 2 : The drier was loaded with 4.8 kgs of chillies. In about 6.5 hours, about 1 kg of moisture was removed. The average value of rise in the temperature of air was found to be 12°C (efficiency = 14%).

Experiment 3 : As a next phase of experimentation, different modifications were made and tests were conducted on the empty drier. The results are as follows :

Duration of the trial = $6\frac{1}{2}$ hours
Max. temperature rise = 12. 5°C
Max. velocity of the air through the drier = 5.3 m/sec

Experiment 4 : The glass cover of the collector was replaced by a transparent PVC sheet 0.2 mm thick. Experiments were conducted to study the performance of the drier. It was found that the performance was almost similar to that of the drier with glass sheet as the cover.

Test duration = 6 hours

Max. rise in the temperature of air = 13°C

Average rise in temperature of air = 11°C

Velocity of air = 4. 4 m/sec.

Experiment 5 : The drier was tested with its bottom covered with polythene sheet. This modification was carried out to study the possibility of increasing the air flow rate. The results, however, showed that there was no improvement in the performance of the drier.

Experiment 6 : As last phase of experimentation, the drier was loaded with 19.6 kgs of chillies. A controlled quantity of 5 kg of chillies were spread for conventional drying. The density of spreading of the control quantity was maintained, at the same level as the density of spreading within the drawers. The results are summarised below :

	Initial weight kgs	Weight after 3 days (kgs)	Weight after 5 days (kgs)
Drier	19.6	10.08	6. 65
Control quantity	5.0	2.35	1. 60

(Drier efficiency = 47%)

Comment :

Result of experiment 6 clearly indicates that the moisture removed by the drier is low when compared to the moisture removed in the case of conventional drying.

5.2.10. **College** : KREC, Surathkal

Project : Solar Dehumidifier

Year : 1978-79

Objective :

To design and fabricate a solar dehumidifier.

Methodology :

1. Different types of dehumidifiers were studied.
2. The disadvantages of dehumidification by vapour compression and the conventional type of chemical dehumidification were discussed.
3. A chemical dehumidifier using silica gel as the moisture absorbent was designed and fabricated.

Description of Equipment :

The dehumidifier consists of a blower, a flat-plate collector, a cylindrical shell and a test chamber, all connected in series by means of a flexible rubber hose. The blower (a 0.25 h.p. portable centrifugal type blower) forces air through the collector. The collector is insulated with a glass cover and it uses a G. I. sheet painted black as the absorber. Air from the collector passes into a cylindrical shell made of MS sheet (diameter of the shell - 450 mm and height 675 mm). The shell contains silica gel (2 kgs), which serves to adsorb moisture from the air. Heat of adsorption is removed by the water pipe coil embedded in the silica gel. Air from the metal shell enters a test chamber made of G. I. sheet. The test chamber is meant for measuring the properties of air at the outlet of the metal shell.

Working cycle : The blower forces the air into the humidifier shell at a constant velocity. In the shell, silica gel adsorbs the moisture in the air. The heat of adsorption is carried along

by the water flowing in the copper tube embedded in the silica gel. During the working cycle, the collector is not used.

Regeneration cycle : After sometime the silica gel gets saturated with water and the adsorption process becomes slow. The silica gel has then to be regenerated. For regeneration, air is forced through the collector, which is now exposed to the solar radiation. The hot air removes the moisture in the saturated silica gel. The silica gel is thus ready for use.

Experiments were conducted by forcing the air through the silica gel bed in the metal tank. The properties of air were measured at the inlet of the metal shell. In some of the experiments a cooling medium, water in this case, was passed through the copper pipes embedded in the silica gel, while in others the cooling medium was not used.

The results are tabulated below :

Air flow rate (kg/min)	Water (coolant) flow rate (kg/min)	Reduction in specific humidity (gm/kg of air)	Reduction in relative humidity (%)	Increase in dry bulb temp (°C)	Decrease in wet bulb temp (°C)
1.1492	—	4.0	19.0	1.0	2.0
1.1492	—	6.5	28.00	0.5	5.0
1.2770	2.0	3.2	9.0	1.5	0.0
1.2770	5.9	7.0	15.5	0.0	3.0
1.2770	20.8	2.47	10.0	1.0	1.0
1.1492	1.6	6.0	8.0	–1.5	3.0
1.1492	1.2	7.0	8.0	–2.5	4.0

Comments :

1. No tests have been conducted to study the performance of the collector, i.e. the collector has not been used to heat air during the regeneration cycle.

2. A cost-wise comparison of the conventional chemical dehumidifier and the new type of dehumidifier using a solar collector has not been made.

5.2.11. College : KREC, Surathkal

Project : Solar solid bed air dehumidifier

Year : 1981–82

Objective :

To design and fabricate a solar solid bed (silica gel bed) dehumidifier for drying air.

Methodology :

1. Different types of dehumidifiers were studied.
2. The disadvantages of dehumidification by vapour compression and conventional type of chemical dehumidification were discussed.
3. A chemical dehumidifier using silica gel as the moisture adsorbent was designed and fabricated.

Specifications :

The dehumidifier is designed to bring down the relative humidity of 10m^3 of air from 75% to 50% in 1 hour.
Area of the flat-plate collector = 1.5m^2
Mass of silica gel used = 6.17 kgs
A centrifugal type blower is used to circulate air through the system (blower capacity 60m^3/hr, $\frac{1}{4}$hp).

Description of Equipment :

The main component of the dehumidifier is the solar collector cum silica gel bed. The dehmidifying chamber consits of two flat-plate collectors placed adjacent to each other and enclosed in a casing (the main purpose behind having two collectors, is that while one collector does the operation of dehumidifing, the other is used for regenerating the silica

gel). Each collector has five wire meshes which are so fixed inside the collector that when the collector is at 27°C, it is designed to absorb maximum solar radiation, and the meshes are in a horizontal position. The wire meshes hold the silica gel crystals. A distributing drum fixed at the bottom of the collector receives air from a room of volume 2.5m^3 and distributes it evenly in the collector. The top receiving end of the collector, collects the air and sends it into the room through two coolers. A centrifugal blower is used to circulate air through the system.

a) Dehumidifying mode : During this mode, the blower forces the air at constant velocity through the collector-cum-dehumidifying chamber. The silica gel adsorbs the moisture in the air and gives out the heat of adsorption to the air. Air then passes through the coolers into the room. (The collector is not exposed to solar radiation during the dehumidifying mode).

b) Regeneration mode : During this mode, the saturated silica gel is regenerated by exposing the collectors to the sun. Sometimes air is forced through the silica gel bed to hasten the process of regeneration.

Performance Figures :

First set of experiments (coolers not used) : Experiments conducted in a room of 2.5m^3 volume.

Air flow rate = 10 m^3/hr, mass of silica gel = 3 kgs

Duration of the experiments = 4 hours

Reduction in relative humidity = 24%

During the regeneration mode, the collector was exposed to the sun and the temperature of the collector was noted at regular intervals. Maximum temperature of the collector was found to be 90°C. Time taken for the regeneration mode was about 2 hours.

Second set of experiments (coolers not used) :

Air flow rate = 35m³/hr ; mass of silica gel = 7 kgs
Duration of the experiment = 1½ hrs ;
Reduction in relative humidity = 26%
Increase in dry bulb temperature = 3°C
Relative humidity at the end of the test ∽ 54%

In another trial, the two collectors were used one after the other for reducing the relative humidity. The min. relative humidity attained was about 22%.

Comment :

1. The experiments to regenerate the silica gel using solar energy clearly show that the maximum collector temperature was about 90°C, which is low when compared to the regeneration temperature of 120°C for silica gel. Some other adsorbent having a low regeneration temperature could have been tried in place of silica gel. Another disadvantage in using silica gel is its high cost (about Rs. 750 for 7 kgs of silica gel).

5.3. SOLAR WATER HEATER

Section

5.3.1. College : RVCE, Bangalore

Project : Collector-cum-storage type of low cost solar water heater

Year : 1979—1980

Objective :

To fabricate and test collector-cum-storage type solar water heaters.

Specifications :

Capacity of the tank = 400 litres
Cross-sectional area of the tanks = 4m² (2 × 2 m)
Height of the tanks = 30 cms

Description of Equipment :

Three tanks of the same size (2m × 2m × 0.3m) have been constructed using different materials (See Fig. 5.2)

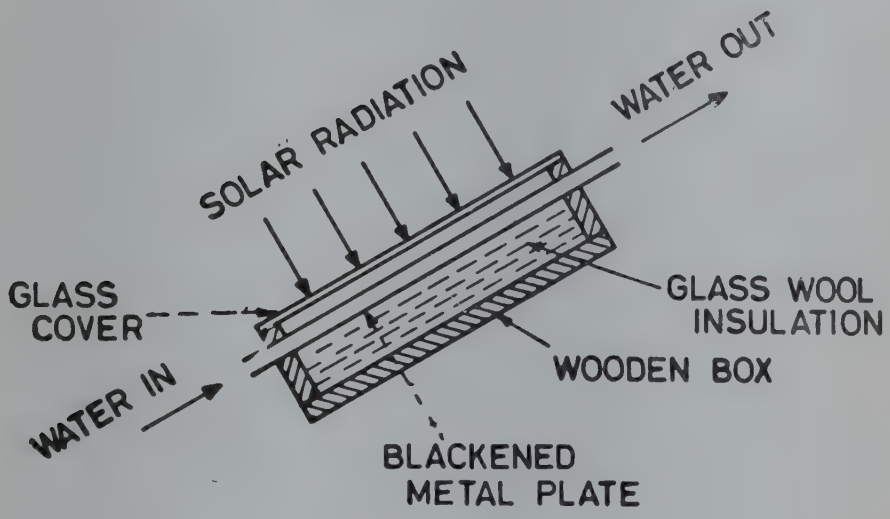

Fig. 5.2 Solar Water Heater

1. Brick wall with cement mortar
2. Brick wall with mud mortar
3. Galvanized iron sheet tank with
   (a) glass wool insulation
   (b) saw dust insulation
   (c) rice husk insulation

Experiments were conducted to (i) compare the performance of the tanks (efficiency-wise and cost-wise comparison), (ii) determine the optimum water depth (for this, tests were conducted by varying the water depth in the tanks from 4 cms to 16 cms in steps of 4 cms. Optimum water depth is that for which a maximum water temperature rise is noted).

Performance figures :

Type of tank	Optimum water depth (cms)	Max. temp. in (C°)	Efficiency (%)	Cost of fabrication (Rs.)
1. Cement	8	48.25	33	720/—
2. Mud Mortar Bank	12	48	33	650/—
3. GI sheet tanks				
(a) glass-wool insulation	12	49	35	1200/—
(b) saw-dust insulation	12	48.5	35	1200/—
(c) Rice husk insulation	12	46.5	31	1150/—

Comments :

1. The experimental results presented in the report do not clearly indicate the relationship between the water depth and the maximum water temperature. In most cases, the difference in the maximum temperature obtained for different depths is very small (about 1–1.5°C).

2. The efficiencies in all cases are low (the maximum value is 35%). Water heaters usually have efficiencies of the order of 45-50%.

5.3.2. College : JCE, Mysore

16. Project : Collector-cum-storage type low cost solar water heater

Year : 1979–80

Objective :

To compare the performances of collector–cum–storage type of solar water heaters, constructed using (i) brick and cement, (ii) M. S. Sheet and (3) Plastic.

Specifications :

Brick and cement tank :

Rectangular tank with dimensions 176 X 116 cm^2
H = 40 one side and 35 cm on the other side.
Max. capacity in litres = 765.6
Cost = Rs. 666/–(with polythene cover)
= Rs. 810/–(glass cover)

M. S. Sheet.

Rectangular tank with drum = 50 X 126 X 20 cm^3 = 126 litres
Cost = Rs. 255.65 (with polythene cover)
= Rs. 288.65 (with glass cover)

Plastic :

Circular diameter = 53.5 cm. at the top
= 46.5 cm at the bottom
H = 23 cm

Volume = 41.28 litres
Cost = Rs. 72/– (with polythene cover)
= Rs. 83– (with glass cover)

Methodology :

1. A study of the availability of solar energy was initailly made.

2. Different types of solar water heaters were studied
3. Keeping in mind the KSCST guidelines, three solar heaters were constructed using different materials
4. The performance of the three heaters were evaluated.

Performance Figures :

Water is filled in the three heaters upto a certain level. The heaters are covered with polythene sheet and exposed to solar radiation. The water temperature and ambient temperatures are noted once in every hour from morning till evening. The procedure is repeated by increasing the water depth by 5 cms in the brick tank and by 2.5 cms in the metallic and plastic tanks. The procedure is repeated using a glass sheet cover instead of a polythene sheet.

Maximum temperature is reached when the depth is 5 cms in all cases.

Type of tank	max temp. attained	efficiency%
1. Brick tank	48.5°C	30—35
2. MS Sheet tank	54°C	30
3. Plastic tank	57°C	25

The temperature rise is more pronounced in case of tanks covered with a polythene sheet.

A plastic tank is more efficient with regard to heat collection ; followed by metallic and cement tanks.

Comments :

1. As the three tanks are of different capacities, a comparison of the performances of the three tanks cannot be expected to yield meaningful results.

2. It has been stated that tanks when covered with polythene sheet, exhibit a superior performance than when

covered with a glass sheet. The experiments have not been conducted under identical conditions. Experiments with a glass cover were conducted on cloudy days. On the other hand on bright days experiments with polythene cover were conducted.

3. The efficiencies are low when compared with those of other solar water heaters.

5.3.3. College : UVCE, Bangalore

Project : Solar Paddy Parboiling

Year : 1981–1982

Objective :

To design and fabricate a solar paddy parboiling plant.

Specifications :

The unit is designed to handle about 30 kg of paddy at a time. The time required for 30 kg of paddy parboiling is about 4 hours.

Description of Equipment :

The device consists mainly of (i) a tube–in–sheet type flat–plate collector for heating water to the required temperature and (ii) a parboiling tank for carrying out the actual process.

The collector consists of a wooden box insulated on all sides except at the top, which is covered with a transparent glass sheet. The collector uses an aluminium sheet painted black, as an absorber. Six aluminium tubes (12 mm diameter and 1600 mm length) are fastened to the underside of the absorber plate using wire trimmings and aluminium cement. The tubes are connected to two header pipes (18 mm dia and 885 mm length). The header pipes in turn are connected with the parboiling tank through G. I. pipes.

The parboiling tank is a cylindrical tank made of M.S. sheet. It can hold about 30 kg of paddy and 50 litres of water. The tank is insulated on all sides with heat insulating foam. It is kept on a stand so that water can easily flow from the tank into the lower header of the collector. The thermosiphon effect circulates water between the collector and the tank.

Performance Figures :

The parboiling tank was loaded with 30 kg of paddy and 50 litres of water at 1030 H. The whole unit was kept in the sun from 1030 H to 1430 H. The water temperature at the inlet and outlet of the collector was recorded at regular intervals. At 1430 H, the paddy was removed from the tank and dried in the sun.

The following table gives the temperature of water recorded between 0930 H and 1430 H.

Time in hours	Outlet temperature (°C)	Inlet temperature (°C)
0930	35	28
1030	55	44
1130	66	64
1230	69	67
1330	63	67
1430	64	60

(Efficiency = around 50%)

Comments :

1. Design details of collector have not been presented.

2. The cost of the unit is high (about Rs. 3000/-). A plate painted black has been used as absorber and the collector pipes are also of aluminium. G.I. Sheet painted black could have been used as the absorber This would have reduced costs considerably.

5·3.4. College : P. E. S. Mandya

Year : 1978 - 79

Project : Solar water heater for silk industries

Objectives :

1. To make an engineering survey of filatures with a view to acquiring information regading the energy requirements of different silk making proceses.

2. To study the feasibility of using energy for meeting the energy requirements of the silk filatures.

3. To design and fabricate a solar water heater.

Methodology :

1. Eleven silk filatures around Chennapatna in Bangalore District were chosen for study.

2. Data was collected by interviewing the owners of the filatures. The data included details regarding

   i) the various sources of energy consumed/year
   ii) quantity of water required for different operations, temperature of water etc.
   iii) quantity of silk produced/day
   iv) quantity of silk, and
   v) quantitiy of waste silk produced/day

3. After analysing the data, the feasibility of using solar energy for meeting the energy requirements of different processes was discussed.

Description of Equipment :

After studying different types of water heaters, a solar water heater making use of a tube–and–sheet type of flat-plate collector was designed and fabricated.

Description of the water heater : The water heater is designed to supply about 100 litres of water per day at a temperature of about 45 °C. It consists mainly of a tube and sheet type of flat - plate collector and a storage tank. The collector consists of an insulated wooden box with a glass cover at the top. It uses a GI Sheet (area – 2.11 m_2) as the absorber. 30 GI pipes of 3.8 cm diameter are used as headers. The collector conducts, by menas of GI pipes, with the storage tank. The storage tank of square cross – section (60 cm x 6 cm) can hold about 120 litres of water. The thermosiphon effect enables the circulation of water between the collector and the storage tank.

Performance Figures :

a) Field study :

1. The main sources of energy for the filatures were found to be (i) charcoal, (ii) firewood and (iii) paddy husk. The annual consumption of these energy resources is found to be (i) charcoal 1 to 5 ton (ii) firewood 3 12.5 tons and (iii) paddy husk 3 to 35 tons.

2. The total quantity of water required for different processes was found to vary from 2600 litres/day to 6000 litres per day. Water at temperatures of

45 to 50 oC, is required for the reeling unit. Hot water at 90–55 oC, is required for cooking, and stifling.

3. Solar water heaters making use of flat plate collector could be used to supply hot water at 45°C to the reeling units. Solar water heaters making use of concentrating type collectors could be used to supply water at 90–95 °C to the cooking and degumming units.

b) Experiments on solar water heater :
No performance studies have been conducted on the water heater.

Comment :

1. The performance of the solar water heater has not been studied.

2. Solar water heaters are suitable for only large scale applications. It is found in practice that solar water heaters are suitable for supplying hot water at 45–50°C.

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6. Forum

This forum attempts to address both students and faculty on topics covered by 'Perspectives in Technology'. Questions may be addressed to Editor, Perspectives in Technology, KSCST, IISc., Bangalore–560 012. A few sample questions have been raised and answered here.

Question :

1. Can a Silicon Photocell be calibrated using an incandescent lamp, to measure solar energy ?

Answer :

Suppose one has a 25W tungsten filament lamp. If a solar cell were kept some distance away, and the readings taken were correlated with the solar irradiance, it would indeed be very good. But unfortunately this cannot be done for quite a few reasons. Let us see why :

a) Firstly, the silicon detector has a very complex spectral response –i.e., if radiation of unit intensity, in one spectral region say at 0.500μm and another say at 1.3μm fall on the detector ; the output will be totally different, being zero at 1.3μm and large for 0.5μm, because the spectral response is zero outside of 0.4 to 1.2μm region, and even in this region it is not flat. The solar spectral distribution, resembles that of a black body at 5,700°K, while the tungsten lamp will have a spectrum corresponding to a grey body at 1800 or 2000°K. A high intensity tungsten-halogen lamp would have a spectrum of a grey body at 3100°K. We know from Wien's law that while the peak output from the sun is at 0.5μm, the lamp output will have peaks at either 1.5μm or 0.95μm. So the silicon photocell will register a different output, even if light of the same power is falling on it, from these three sources.

b) If the lamp is turned on, and the silicon photocell put in front of the lamp, it will be noticed that the reading increases as the photocell is brought closer. This is because the radiation which originates at the source spreads over an ever increasing area, as it moves farther away from the source. If we have a point source emitting uniformly in all directions, (a Lambertian source) the irradiance (i.e. power/unit area, steradian) falls off as $1/r^2$, with 'r' being the distance from the source. This $1/r^2$ law is valid for the sun also. Since we are so far away, moving few kilometers closer or further away, does not register any significant change.

c) The wattage of the lamp has no relation to its radiation output. The wattage merely indicates the electrical power consumed by the lamp and the radiation output depends on the efficiency with which the lamp converts electricity to radiation. Incandescent lamps have very low conversion efficiencies ranging from 1 to 5%.

d) Hence, for calibration, these lamps are totally unsuitable. In order to calibrate the detector either one has to have a lamp or a black body source which simulates the sun's spectral distribution, or a calibrated source of spectral irradiance. Such a calibrated source is a lamp whose output is accurately calibrated to give the irradiance in watts/cm^2 per spectral interval of say 0.01 μm or so, at a given distance from the lamp. If such a source is available, it is set up at a given distance from the entrance slit of a monochromator, and the detector to be calibrated is placed in front of its exit slit. Now, the detector output can be related to the input irradiance, if the monochromator transmittance is known at every wavelength. It is seen that calibration with a lamp is a fairly involved process and needs many sophisticated devices.

e) An easier technique, is to use the sun as the source and a calibrated detector like a pyranometer for deriving the

calibration factor. Keeping both the pyranometer and the silicon photocell, facing the sun together the calibration factor can be determined by following an analytical procedure, like that detailed in reference [8] and [9].

Question :

2. Can plastics replace glass as a transparent cover material, for solar collectors ?

Answer :

The most common plastics which could be used in light transmitting applications are acrylics, polyethyelene, polycarbonate, polyvinylchloride (P. V. C.), Tedlar,(P. U. F.), polytetrafluroethylene (Teflon), and glass-fibre reinforced polyster (GRP). Due to their low density, optical clarity, a high strength to weight ratio, and high impact resistances, plastics are preferred to glass. Visible light transmission in the case of acrylics, is 91 to 93%, in the case of polycarbonate and GRP it varies from 76 to 85%.

The main disadvantage with plastics is their poor durability. Surface of plastics deteriorate due to scratching during installation, and by exposure to the environment. Scratching can be caused by airborne particles harder than plastics or while cleaning the surface of these plastics. Scratches on plastics degrade their optical properties. Natural weathering causes further deterioration in optical properties. Plastics are sensitive to ultraviolet (UV) radiation and degrade on long exposures to UV radiation. A polyethyelene sheet of 16 gauge, will last for 3 to 4 months, if exposed to the sun's radiation, and it softens and sags at temperatures between 80 and 100° C. An acrylic sheet (3mm) will last much longer, as it is more resistant to UV radiation. To retard polymer degradation, UV absorbers are added in plastic formulations. There are compounds such as substituted benzophenons, benzotriazoles and acrylonitriles, that selectively

absorb harmful radiation and convert it to heat energy. Pigments such as titanium dioxide and zinc oxide are also used to protect plastics against the harmful effect of UV. UV treated plastics are not commonly available in the country. Some plastics like Tedlar and Teflon have excellent weathering characteristics and they have been used successfully as transparent covers. Again, thin films of these materials, suitable for use as covers are not easily available in the country.

Question :

3. Can plastics be used in solar energy applications?

Answer :

Plastics have various solar energy applications such as :

1. Outer casing for solar collectors
2. Transparent covers for solar collectors
3. Plastic pipes
4. Thermal insulation
5. Plastic storage tanks

As mentioned earlier, the cost of solar collectors is directly dependent on its weight. Plastics being light, with a high strength to weight ratio can be used for the outer casing of solar collectors. Plastic pipes can be used wherever the temperatures involved are below 80° C. These pipes could either be transparent coils, carrying blackened water or black pipes carrying normal water. They soften at temperatures above 80° C. Plastic foams are polymer based materials which are light in weight, versatile, and they can be used as thermal insulation. Rigid foam, thermocole (polystyrene), insulation

can stand temperatures upto 100° C, while polyurethane foam can stand temperatures upto 150° C, and above. Storage tanks made up of specially treated rigid PVC, are best suited for storing hot water, as they are resistant to corrosion and lighter in weight, than the mild steel tanks. Another innovation is the use of fibre reinforced plastics for casing, structure, tanks, etc.

Question :

4. What would happen to the solar collector if there is no water in the storage tank?

Answer :

Usually a solar panel is connected to a well insulated storage tank and hot water is drawn off regularly from the storage tank. If the tank is empty in the morning, the solar panel will start heating the air inside the collector. As the top glass cover is sealed to the collector box, the temperature inside may rise to 100–120°C, which would lead to breakage of the glass and the black coating of the absorber may also peel off. Sometimes, a little water left in the collector may be converted to high pressure steam, which can lead to dangerous consequences. Hence, it is very essential that water be always left inside the collector at all times.

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3. Design and fabrication of Solar Cooker, MSRCE, Bangalore, 1978–79
4. Design and fabrication of Modified Solar Still, MSRCE, Bangalore, 1978–79
5. Solar Cooker, BVBCE, Hubli, 1978–79 and 1979–80
6. Project Report of Solar Paddy Drier, RVCE, Bangalore, 1978–79
7. Solar heated air for grain drying, BMSCE, Bangalore, 1978–79 and 1980–81
8. Design of cold storage unit using solar energy, NIE, Mysore
9. Utilisation of Solar Energy and fabrication of Solar Cookers, SJCE, Mysore, 1978–79
10. Solar Cooker and Water Heater, MCE, Hassan, 1979–80
11. Solar Still, SIT, Tumkur, 1978–79
12. Design and fabrication of Solar Refrigerator, SIT, Tumkur, 1978–79
13. Utilisation of Solar Air Heater for Agricultural Produce, PESCE, Mandya, 1978-79
14. Solar Water Heater for Silk Industries, PES, Mandya, 1978-79

15. Solar Dehumidifier, KREC, Surathkal, 1978-79

16. Solar Grain Drier, KREC, Surathkal, 1978-78

17. Solar Cooker using heat pipe, KREC, Surathkal, 1978-79

18. Utilisation of Solar Energy for refrigeration purposes (a theoretical approach), KREC, Surathkal, 1978-79

19. Collector–cum–storage type of low cost Solar Water Heater, RVCE, Bangalore, 1979–80

20. Solar Heat Pipe Cooker, RVCE, Bangalore, 1979-80

21. Performance Study of Solar Paddy Drier, SIT, Tumkur, 1978-79

22. Solar Pump, SIT, Tumkur, 1979–80

23. Solar Refrigerator, SJCE, Mysore, 1979-80

24. Solar Water Heater SJCE, Mysore, 1979-80

25. Fabrication of heat pipe type Solar Cooker, SJCE, Mysore 1979-80

26. Design and fabrication of Solar Still, BEC, Bagalkot' 1979–80

27. Design and fabrication of Solar Cooker, BEC, Bagalkot, 1979–80

28. Design and fabrication of Solar Oven, BEC, Bagalkot, 1980–81

29. Tracking unit for sun basket, BEC, Bagalkot, 1980–81

30. Digital data logger, SJCE, Mysore, 1980-81

31. The solar intensometer, SJCE, Mysore, 1980–81

32. Design, fabrication and performance evaluation of a Solar Drier, BMSCE, Bangalore, 1980–81

33. Solar Paddy parboiling, UVCE, Bangalore, 1981–82

34. Design and fabrication of Solar Water Heater, SJCE, Mysore, 1981–82

35. Performance Study on Solar Cooker, GBDT, Davangere, 1981–82

36. Solar autoclave, GBDT, Davangere, 1981–82

37. Solar Solid Bed Air Dehumidifier, KREC, Surathkal, 1981–82

38. Solar Refrigeration using zeolite (a feasibility study), SIT, Tumkur, 1981–82

39. Solar Furnace, BEC, Bagalkot, 1981–82

40. Solar Powered Stirling Engine, BEC, Bagalkot, 1981-82

9. Constants and Conversion Factors

Universal Physical Constants

h = Planck Constant = 6.6256 = 10^{-34} Joule Sec.

R_u = Gas constant = 8.314 Jouls°/K Mole

k = Boltzmann constant = 1.3805×10^{-23} Joule/°K

σ = Stefan Boltzmann Constant = 5.87×10^{-8} Joule/m^2 sec^0K^4

b = Wien Displacement Constant = $2.8978 \times 10^3 m^0K$

c = Velocity of light 2.99792 = 5×10^8m/sec

e = Electron Charge = 1.6021×10^{-19} C or J/V

IAMU = 1 atomic mass unit = 931. 478 MeV

= 1.66042×10^{-27} kg = 4.147 kwh

m_e = Electron Rest mass = 9.1086×10^{-31}kg = 5.486×10^{-4} AMU

m_p = Proton Rest mass = 1.6725×10^{-27}kg = 1.007277AMU

N_A = Avagadro Number = 6.0225×10^{23} molecules/gm-mole

Other Constants

g_s = Standard acceleration of gravity = 9.80655 m/sec^2

Density of air = 1.293 kg/m^3 at STP

Density of water = 999. 972 kg/m^3 at 3.98°C, 760 mm Hg

Velocity of Sound = 331.7 m/sec in Air (STP)

= 1470 m/sec in water (20°C)

Conversion Factors

Mass : 1 kilogram = 1 kg = 1000 grams = .001 Metric tons
= 2.205 pounds-mass = 0.001102 short tons
= 6.023×10^{26} amu

Length : 1 meter = 1 m = 1000 millimeters = 10^6 micrometers
= 39.37 inches = 3.281 feet

Area : 1 square meter = $1\ m^2 = 10^{28}$ barns = $10^4\ cm^2$
= $1550\ in^2 = 10.76\ ft^2$
= 2.471×10^{-4} acres = 10^{-4} Hectares

Volume : 1 cubic meter = $1m^3 = 10^6\ cm^3 = 10^3$ litres
= 264.2 U.S gallons = $34.31\ ft^3$

Force : 1 Newton = 1 kg. $1m/s^2 = 1N$
= 1 J/m = 1 kgm/s^2 = 0.102 kp = 10^5 dyn

Work : 1 Joule = 1 N.m = 1 kg m^2/s^2
= 1 Ws = 278.10^{-9} kwh = 1Nm = 0.102 kpm = 0.239 cal

Energy : 1 Joule = 1 J = 10^7 ergs
= 6.242×10^{18} eV
= 0.7376 ft. lbf = 9.478×10^{-4} Btu
= 3.725×10^{-7} hp. h = 2.778×10^{-7} kWh.

Power : 1 Watt = 1 Nm/s = 1 kg m^2/s^3
= 10^{-3} kW = 0.102 kp/m s = 860 cal/h = 0.239 cal/s
= 3413 Btu h = 0.001341 hp
= 6.242×10^{18} eV/s

Pressure : 1 pascal = Pa = 1 newton/square meter = 1 kg/ms^2
= 10^{-5} bar = 0.9867×10^{-5} atm
= 1.450×10^{-4} lbf in^2
= 2.953×10^{-4} in of Hg = 0.004018 in. of Hg
= 0.007502 torr = 0.007502 mm of Hg

Density : 1 kilogram/cubic meter = 1 $kg/m^3 = 10^{-3}$ gm/cm^3
= 0.06243 pbm/ft^3 = 0.008345 lbm/US gallon

Viscosity : 1 poise = 100cP = 0.1 kg/s.m
= 241.9 lbm/ft.h = 0.009029 $lbf.s/ft^2$

Thermal conductivity :

1 W/m.°C = 1 J/(s.m°C) = 1N/(s°C) = 1 kg/m (s^3 °C)
= 0.2388 cal/(s.m.°C) = 0.5778 Btu/(hft^2 F/ft)

Power density and volumetric heat generation rate :

1 W/m^3 1 = $kg/m.s^3$
0.096 = 6 $Btu/h.ft^3$

Specific power and mass heating values :

1kJ/kg = 1 J/gm = 1000 m^2/s^2

= 0.430 Btu/lbm

Heat flux : 1 W/m^2 = 1kg/s^3

= 0.3170 Btu/h. ft^2

Heat transfer coefficient : 1 W/m^2 °C = 1J/(m^2 s°C) = 1 kg/(s^3 °C)

= 0.8598 kcal/(m^2 h°C)

= 0.1761 Btu/ft^2 hF

Standard fuel energy values :

Coal :

Anthracite : HHV = 12,700 Btu/lbm = 29,549 kJ/kg

Bituminous : HHV = 11,750 Btu/lbm = 27,330 kJ/kg

Crude oil : HHV = 18,100 Btu/lbm = 42,100 kJ/kg

= 138,100 Btu/gallon = 5,800,000 Btu bbl

Natural gas (dry) : HHV = 24,700 Btu/lbm = 57,450 kJ/kg

= 1021 Btu/ft^3

Fuel-energy equivalents :

One barrel (42 gallons) of oil = 46 lbm of coal

= 5680 ft^3 of natural gas

= 1700 kW. h of electricity

One short ton of coal = 4.345 bbl of crude oil

= 24,682 ft^3 of natural gas

= 7366 kw.h of electricity

1000 ft^3 of natural gas = 0.176 bbl of crude oil

= 81.0 lbm of coal

= 300kW.h of electricity

10. Glossary and Nomenclature

10.1 Glossary

Absorptance : Absorptivity is the property of absorbing radiation, possessed by all materials to varying extents. Absorptance is the ratio of the absorbed to the incident radiation impinging on the body.

Aerosol : A gaseous suspension of solid or liquid particles.

Air mass : The absolute air mass is the total mass of the scattering and or absorbing substance in the optical path, through which the solar beam radiation traverses and is given by : $\int \rho ds$, ρ being the density of the scatterer/absorber and ds is path along the beam. The "air mass" m, is the relative path m $(A,Z) = \int_A \rho ds / \int_A \rho dh$, with the numerator giving the optical air mass along the beam and making a zenith angle Z to the vertical, while the denominator gives the optical air mass along the vertical direction, both being calcutated from some altitude A. For Zenith angles less than 80°, ds = secZ/dh, so, m (A,Z) = sec θ. The air mass at sea level is related to air mass at any altitude as m (A,K) = p(A)/p(o), where p(o) and ρ (A) are the atmospheric pressures at sea level and at altitude A. The air mass m (0,Z) for any angle Z given by equation 4 in section 2.

Albedo (R_g) : The ratio of the solar radiation reflected from the earth to the total amount of radiation incident upon it is called the albedo.

Attenuation : The reduction of radiation flux over a given path length, due to absorption and scattering is referred to as the attenuation.

Auxiliary heating system : System that acts as a backup to the solar system during extended periods of extremely cold and/or cloudy weather.

Azimuth angle (Solar) : The angle which the horizontal component of the direct sun's rays makes with the true south in the northen hemisphere is the solar azimuth.

Black Body : An ideal body that absorbs all the radiation incident on it, a black body also emits the maximum possible radiation at thermal equilibrium at a given temperature.

Clearness number (K_T) : The ratio of measured direct radiation intensity on a horizontal surface to the computed direct radiation intensity on a horizontal surface for the same altitude of the sun.

Cloudiness index ($\bar{K}_T$) : It is the ratio of long term average daily radiation intensity on a horizontal surface on earth to extra-terrestrial daily radiation intensity.

Collector : Any device gathering the sun's radiation and converting it to a useful energy from.

Collector efficiency (η) : The ratio of the energy collected by a solar collector to the radiant energy incident on the collector.

Collector tilt angle (β) : Angle at which the collector is slanted up from the horizontal plane.

Concentration Ratio (CR) : Ratio of aperture area of the collector to its receiver area. CR = 1 for a flat-plate collector.

Declination Solar (δ) : The angle between the sun's rays and the zenith above or below the direction directly overhead at noon on the earths' equator. In other words it has the numerical value of the latitude, at which the sun is directly overhead at noon on a given day. Declinations north of the equitorial plane are positive, while those in the south are negative.

Diffuse radiation (d) : Scattered radiation from the sun that falls on a plane of stated orientation over a stated period ; in the case of an inclined surface, the radiation reflected from the ground is also inclined.

Direct (beam) radiation: Radiation from the sun received from a narrow solid angle measured from a point on the earth's surface.

Emmisivity (ε) : It is the ratio of the emissive power of a given surface to the emissive power of a black body at the same temperature.

Extinction coefficient (κ) : The sum of absorption and scattering coefficients, defined as $dI = -\kappa I dx$

Glazing : Glass, plastic or other transparent covering of a collector absorber surface.

Global radiation : The total of diffuse and direct radiation is also known as total or net radiation.

Grashof number (Gr) : The ratio of buoyancy force to the viscous force. $= g \beta \Delta T L^3./\nu^2$

Greenhouse effect : A heat transfer effect wherein heat loss from a surface is controlleed by suppresing the convection loss; incorrectly attributed to suppression of radiation from an enclosure.

Heat pipe : A passive heat exchanger, employing the principles of evaporation and condensation, to transfer heat at high levels of effectiveness.

Heliostat : Device to direct sunlight towards a fixed target.

Infrared radiation : Radiation beyond the red end of the visible spectrum, 0.7μm but shorter than the microwave radiation (i.e. upto about 300μm).

Integrated systems : The installation of solar energy systems as a part of the structure.

Intensity (I) : The radiant energy falling per unit time

on a unit surface held normal to the direction of radiation, contained in a unit solid angle and unit wavelength interval.

Irradiance : The radiant energy falling per unit area per unit time on a plane surface.

Laminar flow : A flow in which the fluid particles follow smooth streamlines and there is no obvious mixing between adjacent layers of fluid.

Latent heat : Internal energy change required to effect a phase change.

Latitude (L) : Angular distance of place north or south from equatorial plane measured in degrees.

Local Solar time : Astronomical time at which the sun always crosses the true north–south meridian at 12 noon. This time is different from the local time depending on longtude, time zone and the equation of time.

Longwave Radiation : Refers to thermal radiation emitted by terrestrial objects, emitting radiation at wavelengths longer than that of the sun ($\lambda > 3\mu m$).

Nusset Number (Nu) : It is the ratio of convection heat transfer to heat transfer by conduction.

$$Nu = h_c \frac{1}{K}$$

Passive systems : Systems using the sun's energy without mechanical systems.

Payback period : Length of time required to recover the investment of a project by benefits accruing from the investment.

Possible sunhine hours (D) : The number of hours from sunrise to sunset.

Power tower : A tower placed so that the reflected

direct radiation from the heliostat mirrors can be focussed onto a receiver at its top. Heat exchange takes place at the top of the tower.

Prandtl number (Pr) : The ratio of momentum diffusivity to the thermal diffusivity

Rayleigh Scattering : Occurs when the size of the particles are much smaller than the incident wavelength. Scattering is a fundamental physical process associated with light and its interaction with matter. It occurs at all wave lengths covering the entire electromagnetic spectra.

Refractive index (n) : The ratio of the velocity of light in free space to that in the material.

Relative humidity : The ratio of the amount of water vapour actually in the air to the amount that would saturate the air at that same temperature, and expressed as a percentage.

Retrofit : The installation of solar energy systems in already existing structures.

Reynolds number (Re) : The ratio of the fluid dynamic force or inertial force to the viscous drag force $\rho V D_h/\mu$

Selective Surface : A surface which has high absorptivity for the solar range of wavelengths and low emissivity for the thermal range of wavelengths.

Short wave radiation : Solar radiation which has most of its energy in the range 0.1 to 3μm.

Solar Constant (I_{sc}) : The amount of solar radiation received by a surface normal to the sun's rays per unit area per unit time, beyond the earth's atmosphere at the mean earth-sun distance.

Solar Hour Angle : Is measured in degrees and is equal to 15 times the number of hours from the local solar noon.

Values east of due south (i.e. morning values) are positive and values west negative.

Solar noon : The local time at which the sun is highest in the sky.

Spectral energy distribution : A curve showing the variation of spectral irradiance with wavelength.

Sunrise Hour Angle : The hour angle when the sun appears just above the horizon : h_{sr} ($Z = 90°$) = h_{ss}($Z = 90°$) h_{ss}: the sunset hour angle.

Thermal conductivity (K) : The quantity of heat transmitted per unit time per unit area per unit temperature gradient.

Thermopile : A large number of thermo-couples connected in series.

Transmissivity (J) : The ratio of the transmitted radiation to the incident radiation impinging on the body.

Trombe walls : A thermal storage mass which is a part of the building used as a passive collection devise.

Ultraviolet radiation : Radiation shorter than the blue end of the visible spectrum, $\lambda < 0.4\mu m$, but larger than X rays, i.e. upto about $0.1\mu m$.

Visible radiation : Radiation in spectral interval 0 4 to $0.7\mu m$.

Zenith angle (Z) : The angle which the direct sun's rays make with the vertical.

10.2 NOMENCLATURE

10.2.1 (CHAPTER 2)

I_{sc} — Solar Constant (W/m^2)

Z — Zenith angle

λ — Wavelength (μm)

C_1 — Absorption coefficient

C_2 — Rayleigh scattering coefficient

C_3 — Attenuation coefficient

I_g — Global radiation (W/m^2)

T — Transmittance

A — Altitude above sea level

H — Average total radiation on a horizontal plane

H_o — Extra-terrestrial total radiation on a horizontal plane

n — Duration of actual sunshine hrs.

N — Duration of possible sunshine hrs.

D — No. of possible sunsrise hours per day (i. e. number of hours from sunshine to sunset)

a,b — Constants

K_T, $\overline{K_T}$ — Clearness number, Cloudiness index

d_1 ,d — Diffuse radiation

h_s — Sunset hour angle

h — Hour angle

t — Time of day; t_s sunset time

T — Length of day = 24 hours

I_d, I_T — Diffuse and total solar intensities

L — Latitude

δ — Declination

I_b — Beam radiation

α_s — Solar azimuth angle

α_w — Surface azimuth angle

β — Tilt of the surface

R_g — Reflectivity of albedo of the ground

10.2.2 (CHAPTER 3)

T_s — Transmittance of collector covers

α_s — Solar absorbtance of the collector–absorber plate surface

I_s — Solar irradiation (W/m^2)

A_c — Collector–absorber area (m^2)

h_w — Convective heat transfer coefficient due to flow air over the collector ($W/m^{2\circ} K$) = $5.0 + 3.8V$, V is wind velocity m/sec.

T_p — Collector–absorber plate temperature (°K)

T_{air} — Air or ambient temperature (°K)

ε_p — Plate emittance

σ — Stefan–Boltzman's constant = $5.67 \times 10^{-8} W/m^2K^4$

q_u — Rate of heat transfer from the collector–absorber plate to the working fluid

$\dot{q}_s$ — Rate of internal energy storage in the collector

q_{lc} — Rate of heat transfer (or heat loss) from the collector absorber plate to the surroundings

U_c — Collector heat loss conductance $W/m^2 \cdot K$

U_T — Collector top heat loss conductance $W/m^2 \cdot K$

U_B — Collector back heat loss conductance $W/m^2 \cdot K$.

K_{air} — Thermal conductivjty of air $W/m \cdot K$

L — Space between two surfaces in metres

Gr — Grashof number

Ra — Rayleigh number

Pr — Prandtl number

g — Gravitational constant = 9.8 m/sec^2

β — Coeffjcient of expansion in fluid in K^{-1} = $\beta = \frac{1}{T_{average}}$

ν — Kinematic viscosity m^2/se

α — Thermal diffusivity $\frac{K}{C_p}$ m^2/sec

P_{wa} — Partial pressure of water vapour in atmospher in inches of Hg

R — Thermal resistance (Km^2/W)

t_p — Plate thickness in meters

w — Length of the plate between two pipes in metres

t_b — Bond thickness

k_b — Thermal conductivity of the bond between pipe and plate

l_b — Bond width

t_t — Tube thickness

k_t — Thermal conductivity of the tube

d — Diameter of the tube

h_f — Film heat transfer coefficient

T_{fi} — Temperature of the fluid inlet

G — Flow rate per unit surface area of collector in Kg/m^2-sec.

ρ — Reflectance

κ — Extinction coefficient

NEXT ISSUE

The second issue of 'Perspectives in Technology' will also be on Solar Energy Devices. This issue will be devoted to Solar Refrigeration, Photovoltaic devices, Solar Concentrators and Solar Cookers. Articles are invited from students and faculty. The best article will be published. Students are also requested to pose their doubts on Solar Energy and Solar Energy devices. Articles and questions should be addressed to the Editor, Perspectives in Technology, KSCST, Indian Institute of Science, Bangalore. 560 012. The last date for receipt of articles and questions is 31st October, 1983.

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Articles from faculty and students of the engineering colleges are invited. These articles should not exceed 3,500 words, and should be submitted in triplicate. They should be typed double spaced on A4 size paper. All figures including photographs should be numbered consecutively in arabic numerals in the order of appearance in the text. References should be cited in the text, by serial number. References should be listed at the end of the paper in the following format: Authors name, initials, year of publication, title of publication, publishers. Articles/ papers should be addressed to the Editor, Perspectives in Technology, KSCST, IISc., Bangalore-560 012,

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